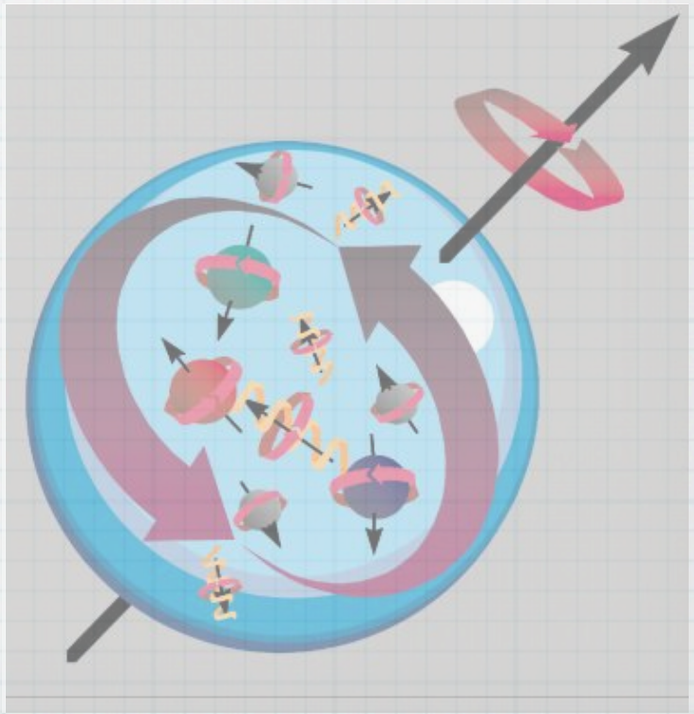
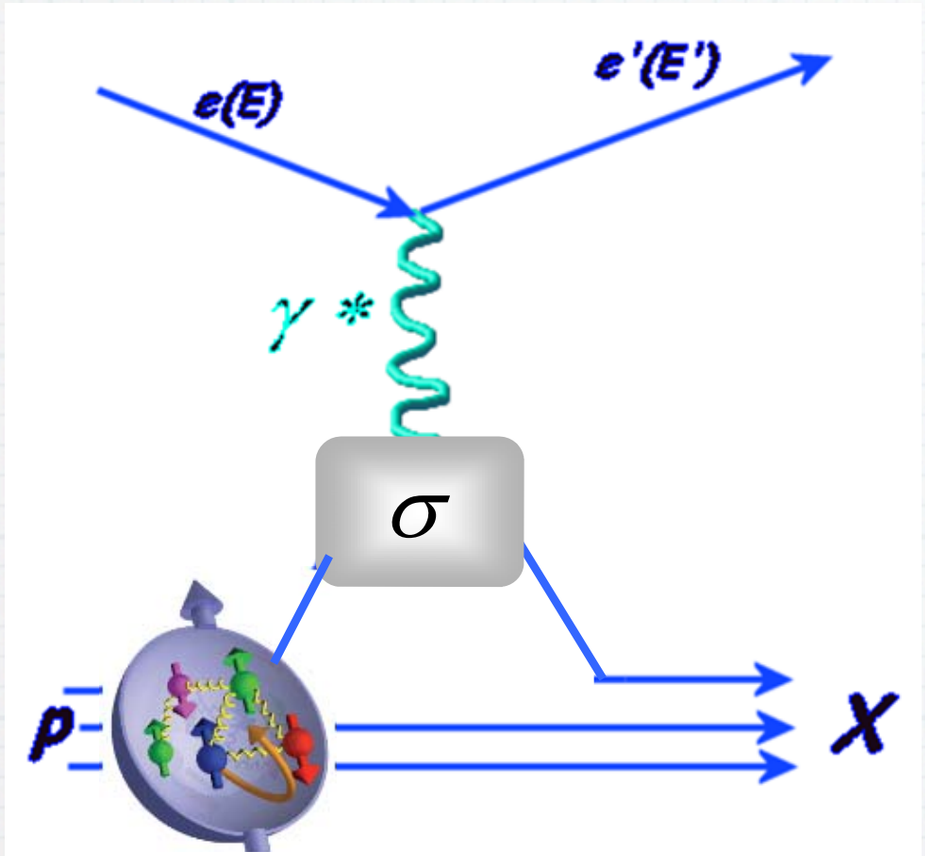
Spin Physics in DIS

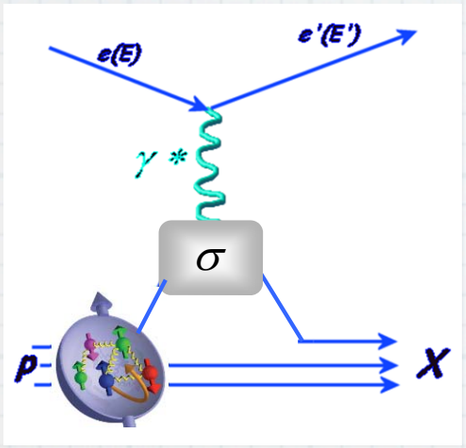
FRANCESCA GIORDANO

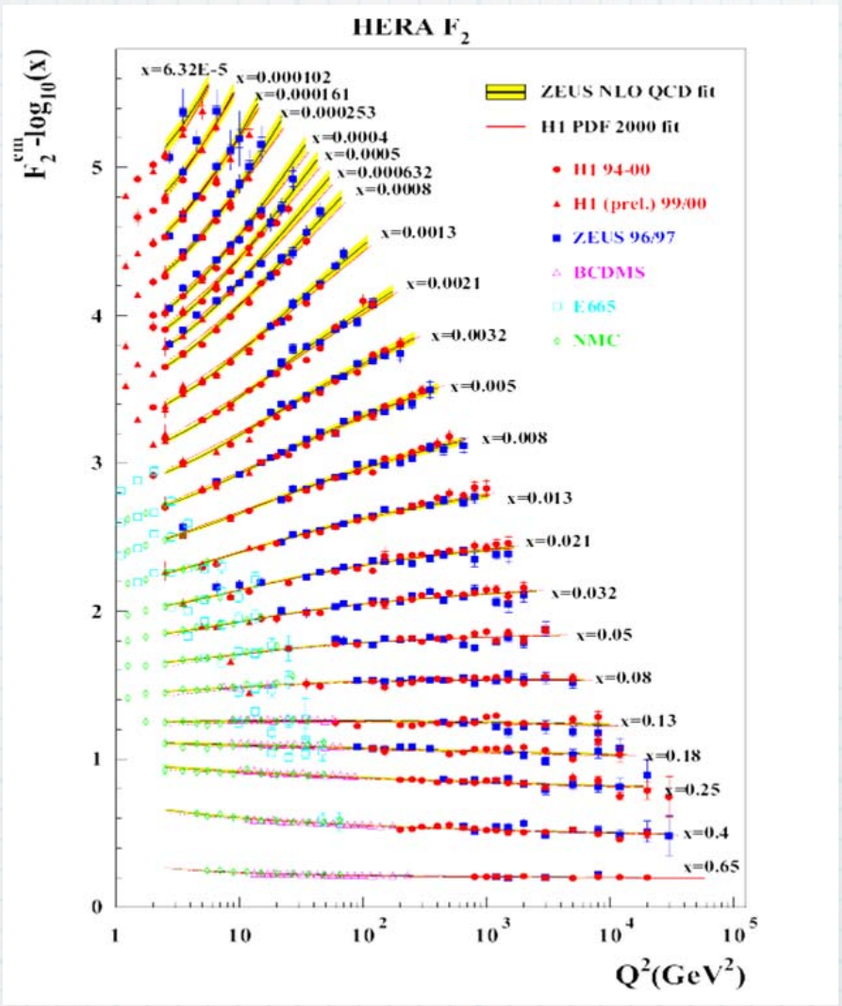
2011 RHIC & AGS ANNUAL USERS' MEETING





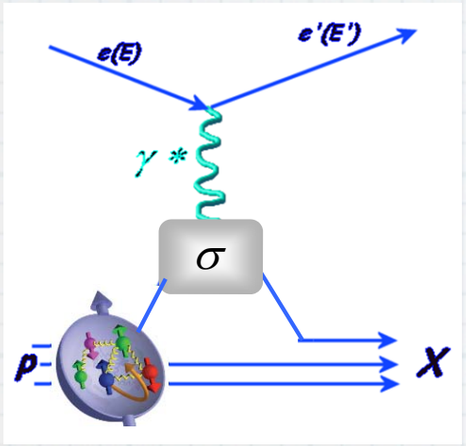
Deep-inelastic scattering

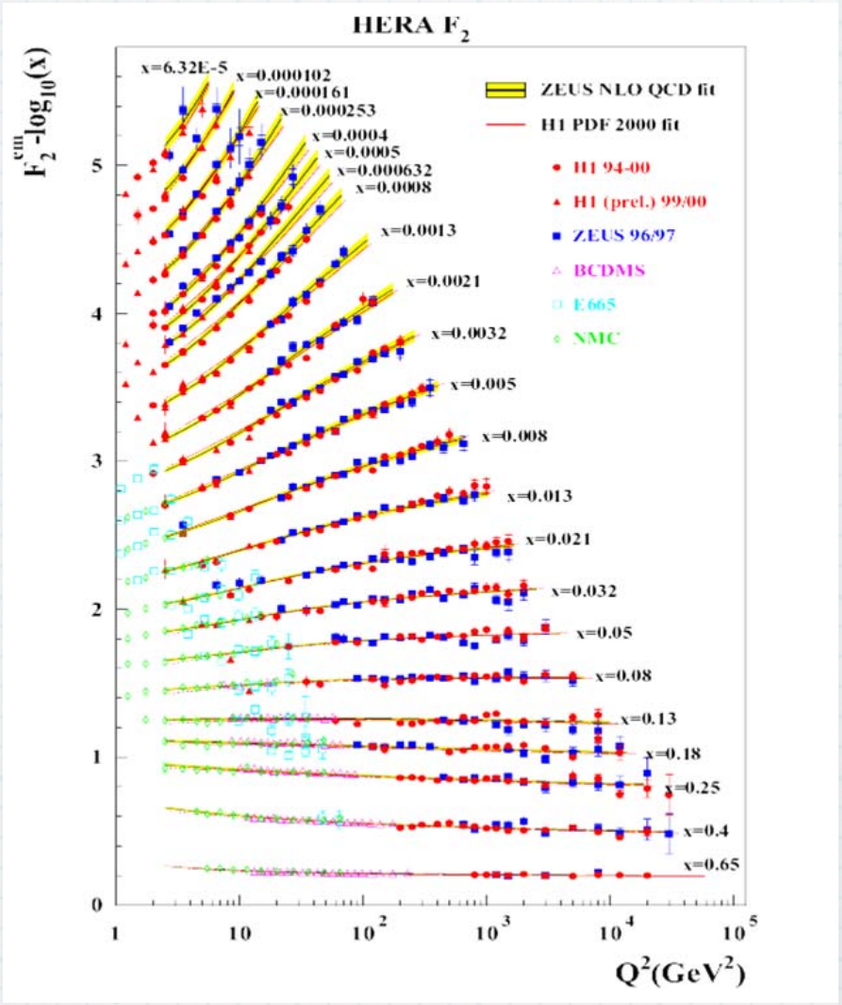




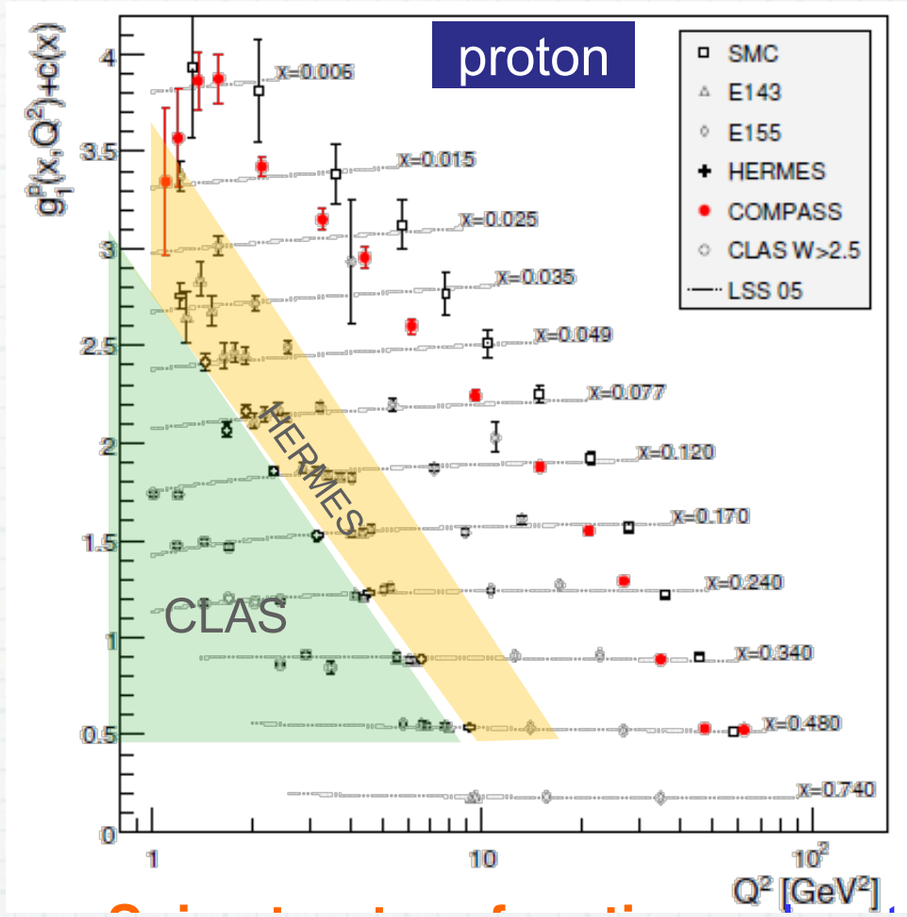
longitudinal momentum structure

Deep-inelastic scattering





longitudinal momentum structure



longitudinal spin structure

Deep-inelastic scattering

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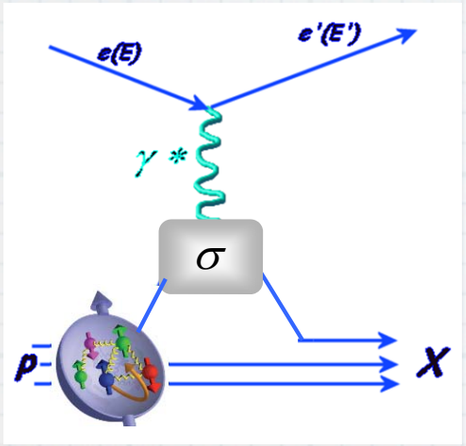
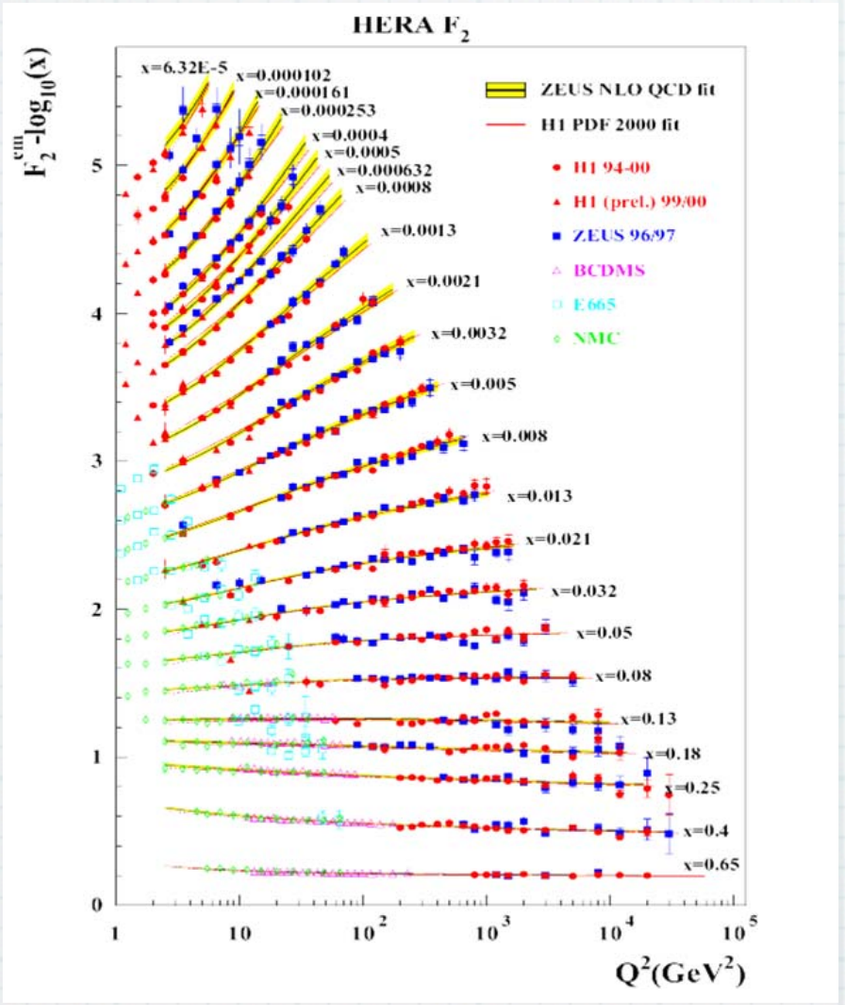
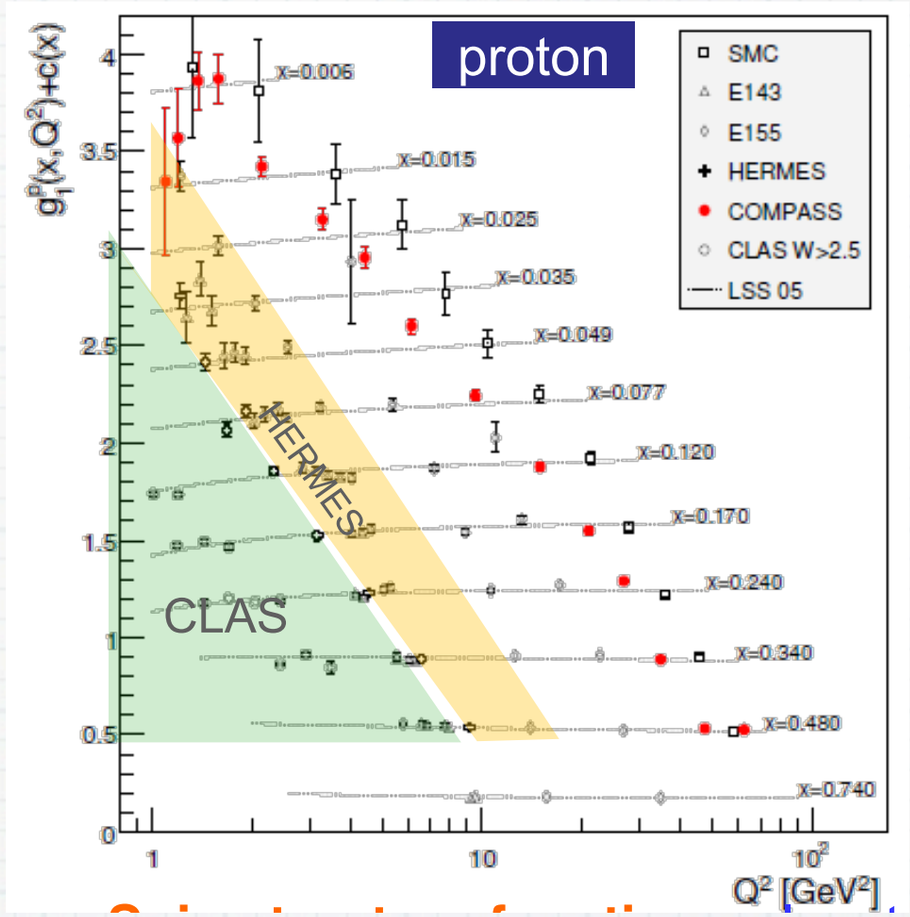




longitudinal momentum structure

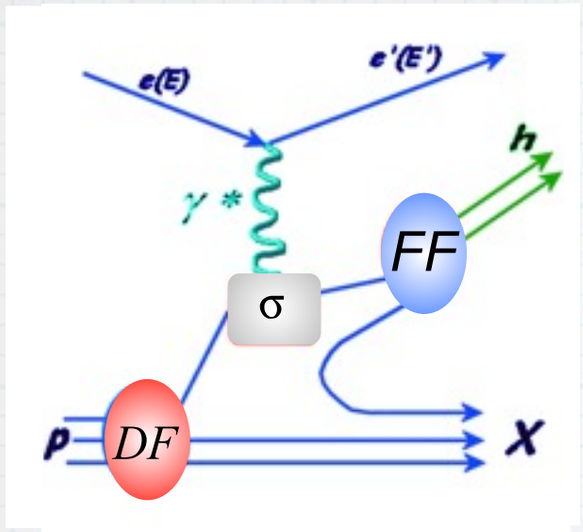


longitudinal spin structure

80s: Spin crisis

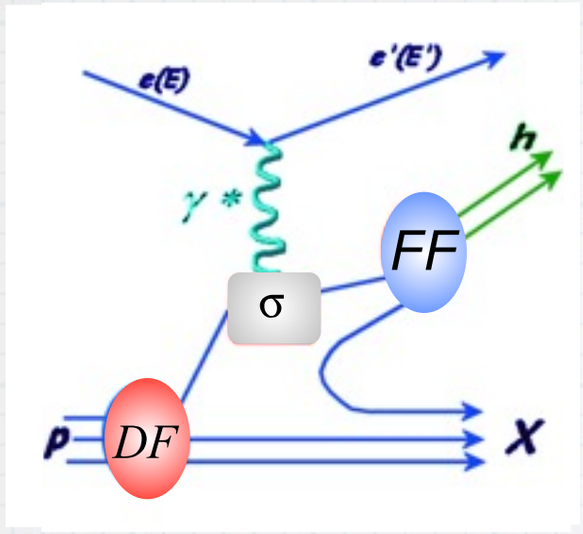
only 30% of nucleon spin is carried by valence quarks

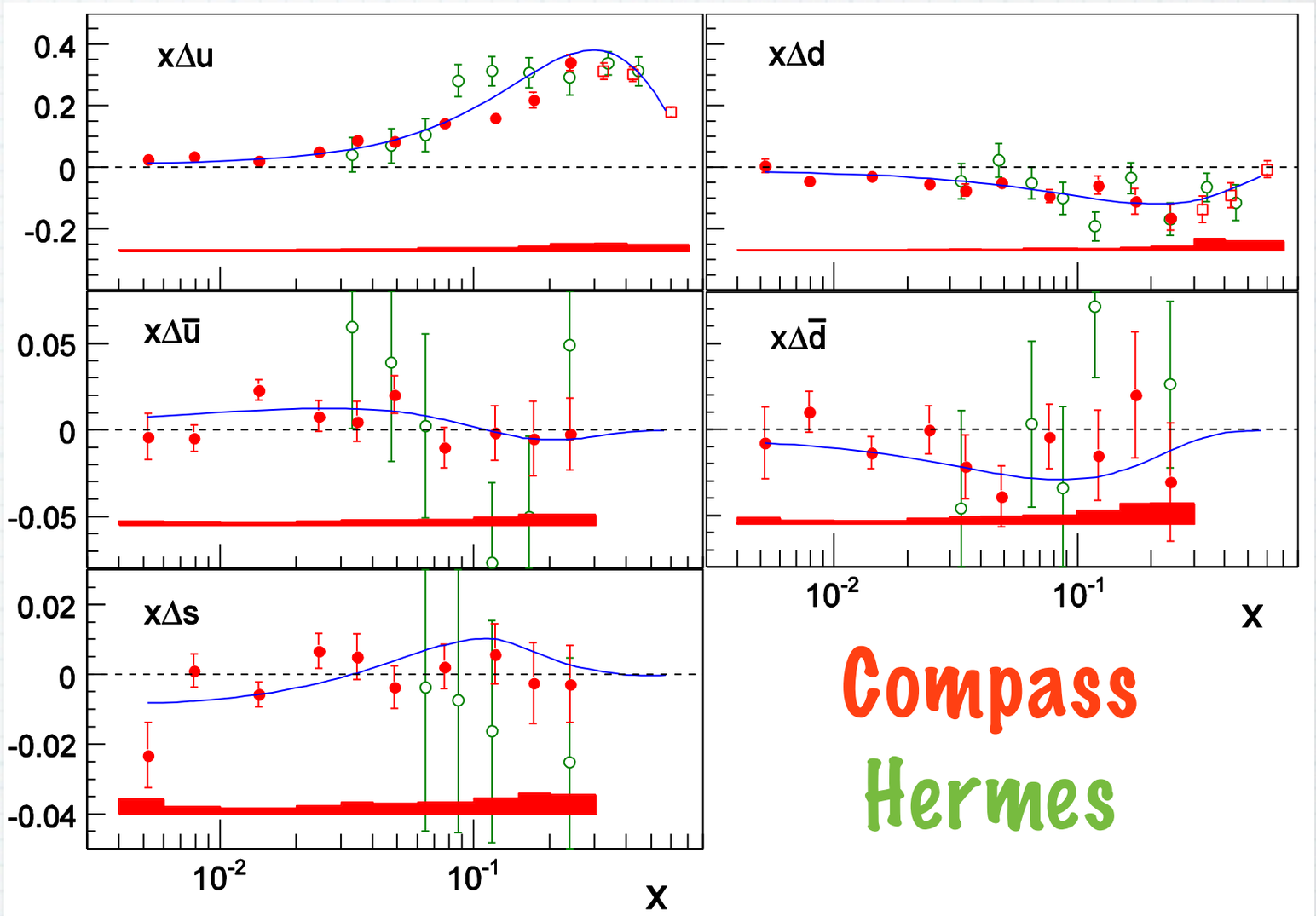
Deep-inelastic scattering



Semi-inclusive DIS

FRANCESCA GIORDANO

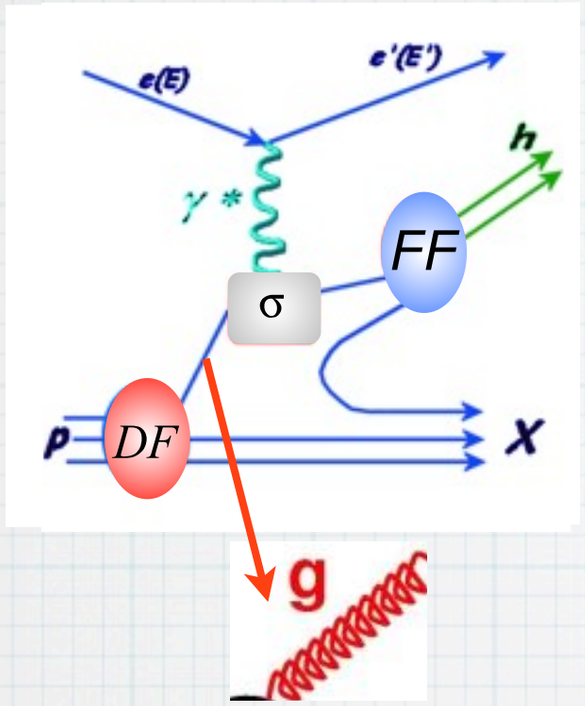


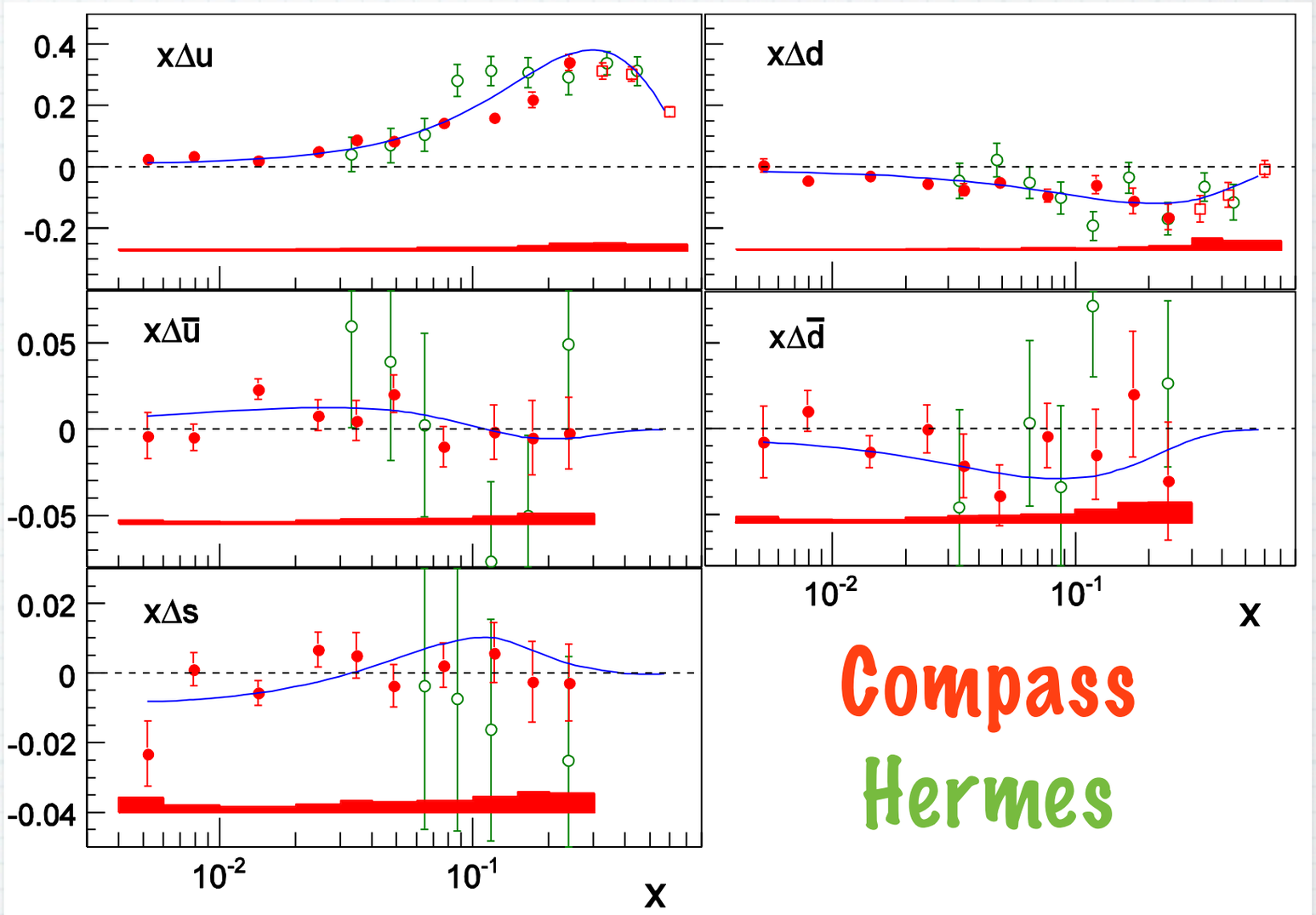


Compass

Hermes

Semi-inclusive DIS

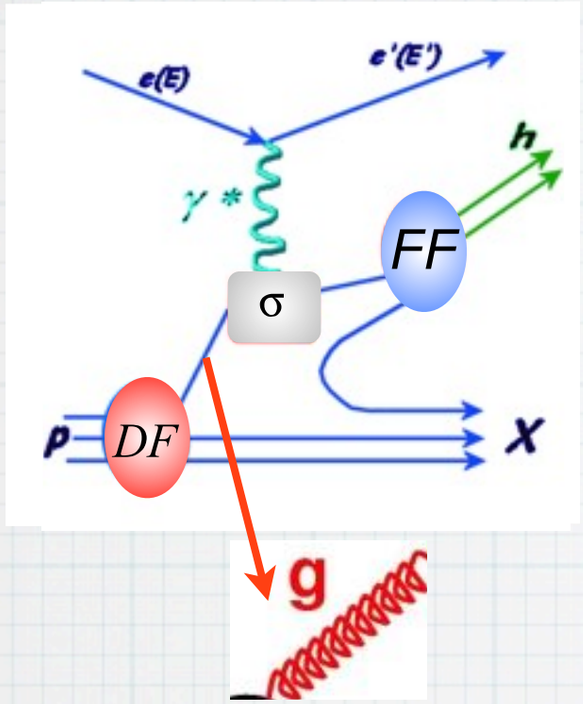


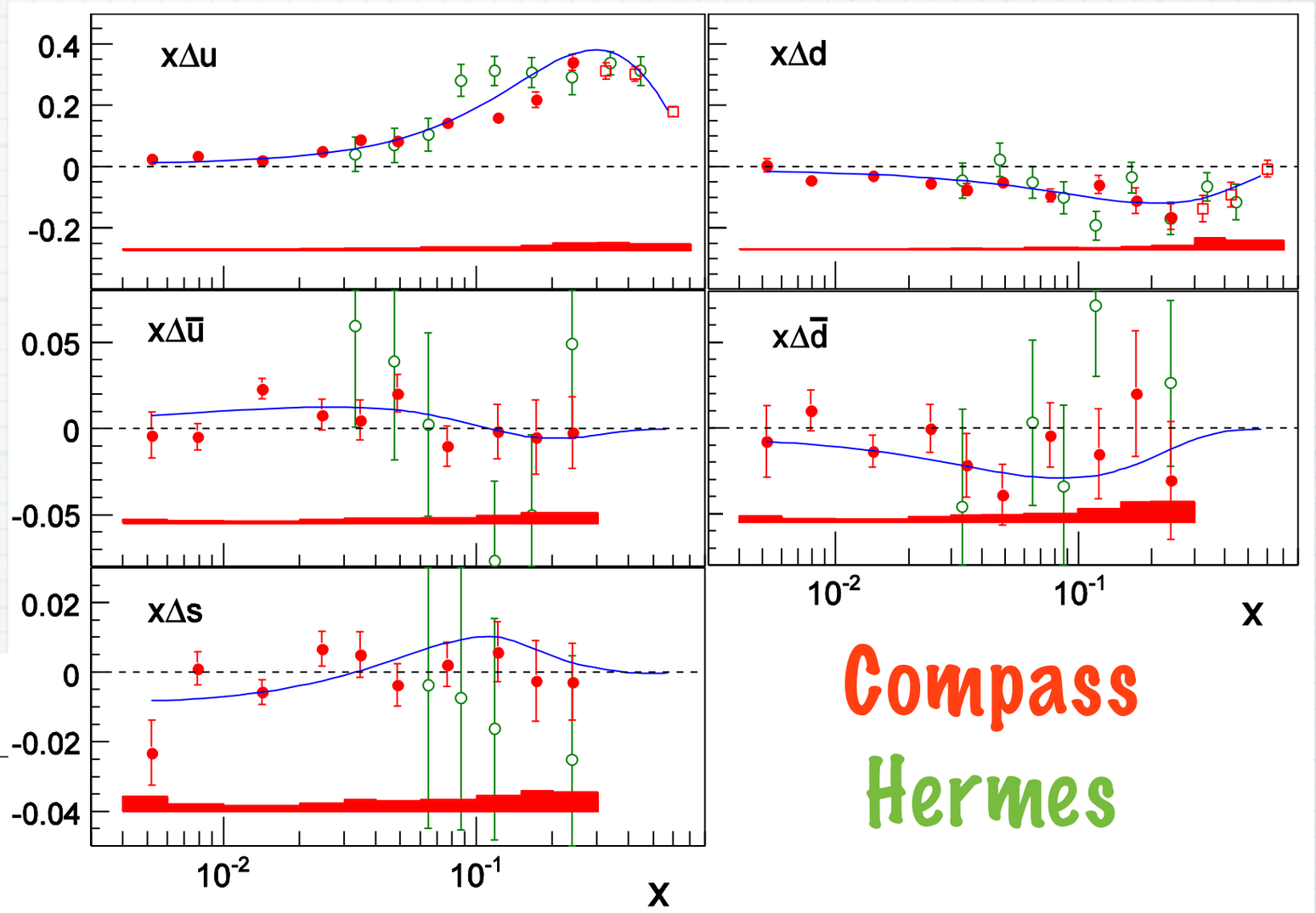


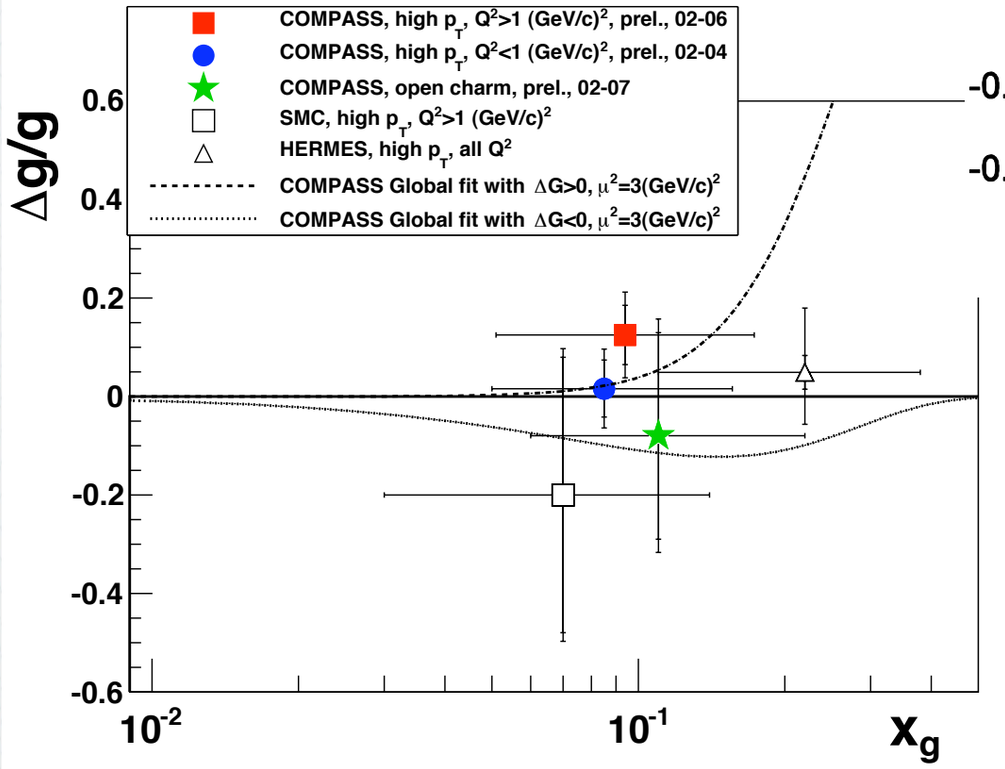
Compass

Hermes

Semi-inclusive DIS







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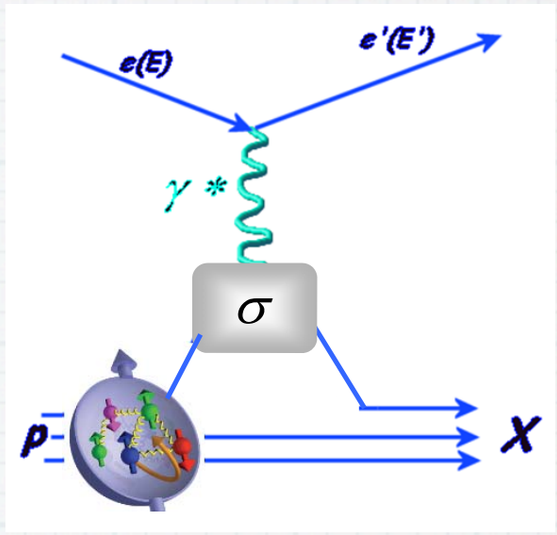
Semi-inclusive DIS



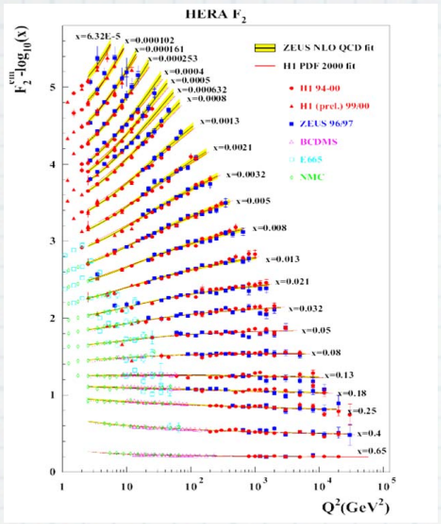
nucleon \ quark	U	L	T
U	f_1		
L		g_1	
T			h_1

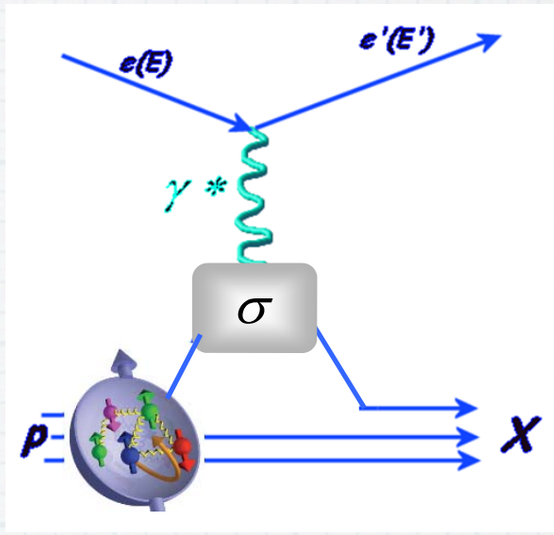
transverse longitudinal

nucleon spin

parton spin

parton transverse momentum





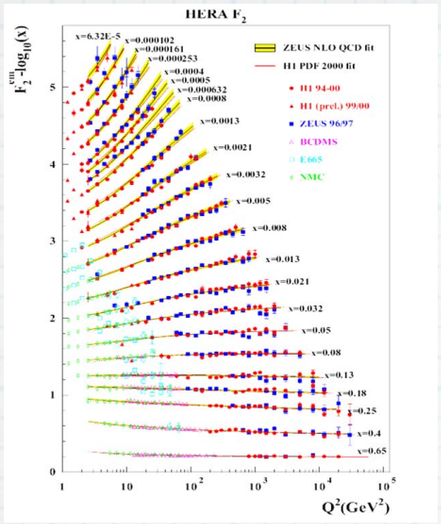
		quark		
		U	L	T
nucleon	U	f_1 ⊙		
	L		g_1 ⊙ − ⊙	
	T			h_1 → − →

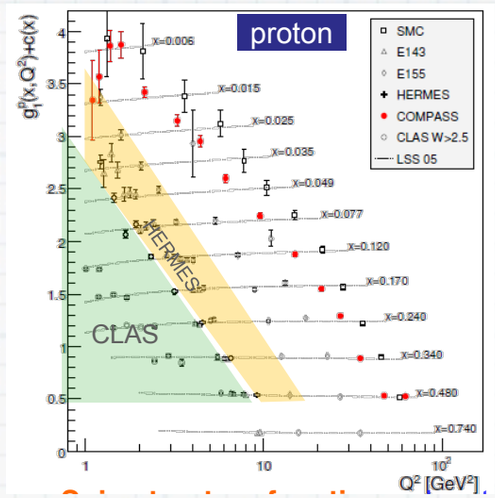
transverse longitudinal

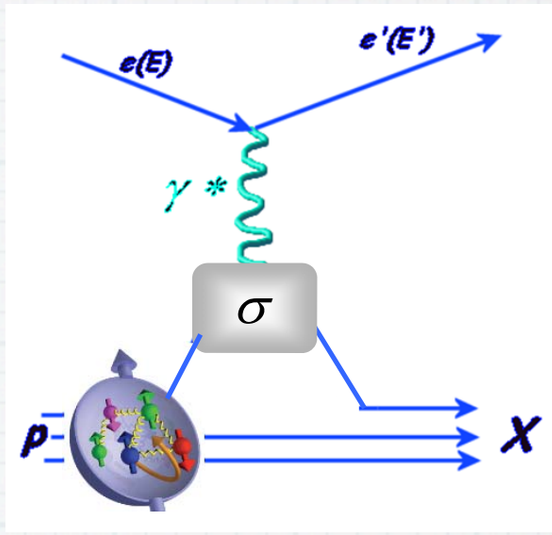
nucleon spin

parton spin

parton transverse momentum







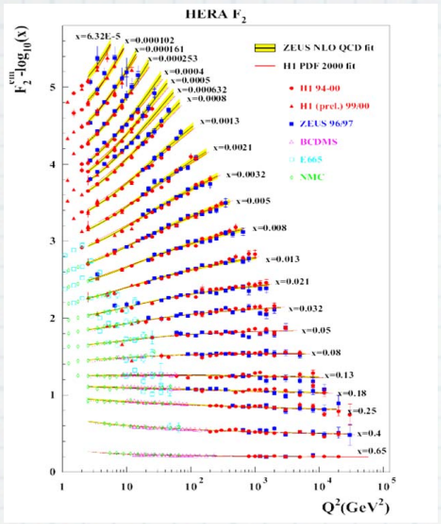
nucleon	quark: U	quark: L	quark: T
U	f_1		
L		g_1	
T			h_1

transverse longitudinal

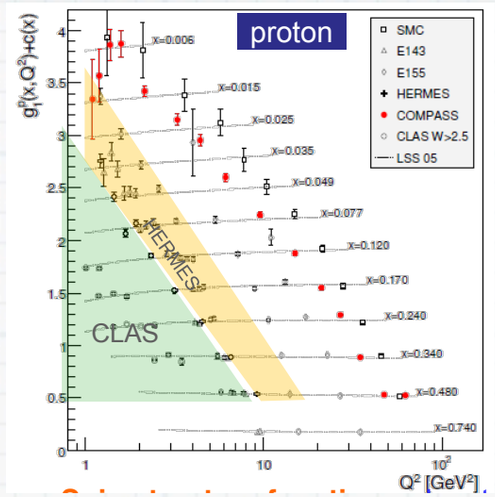
nucleon spin

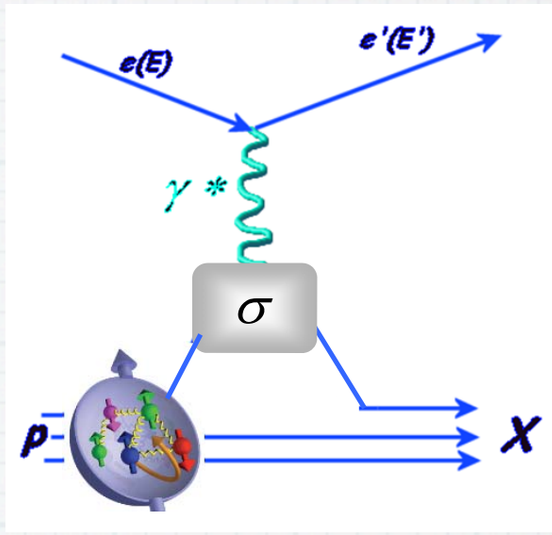
parton spin

parton transverse momentum



but integrated over final states!





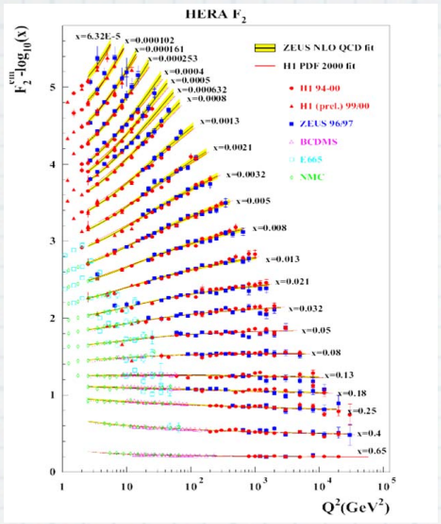
nucleon \ quark	U	L	T
U	f_1		
L		g_1	
T			h_1

transverse longitudinal

nucleon spin

parton spin

parton transverse momentum



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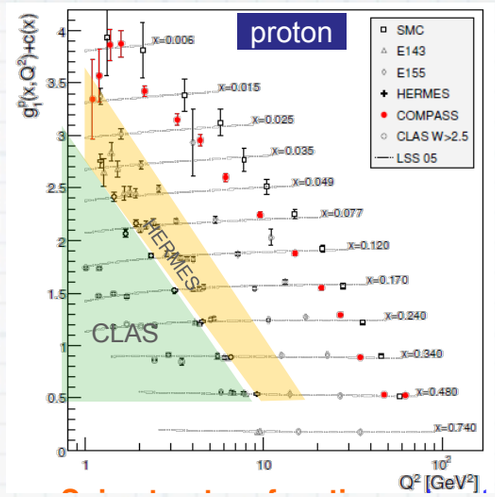

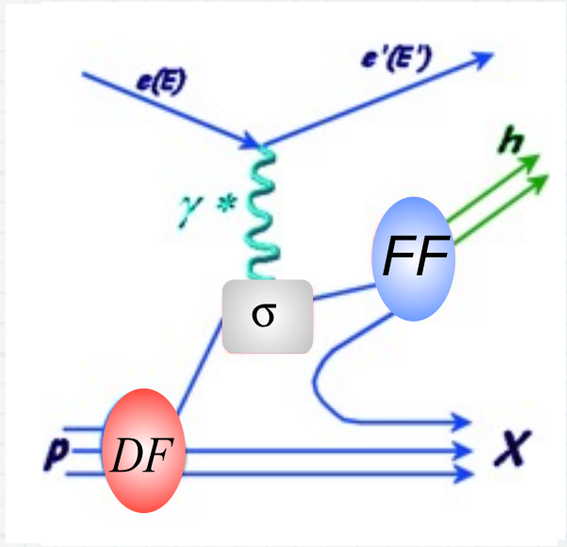

		quark		
		U	L	T
nucleon	U	f_1 ⊙		
	L		g_1 ⊙ − ⊙	
	T			h_1 → − →

transverse longitudinal

nucleon spin

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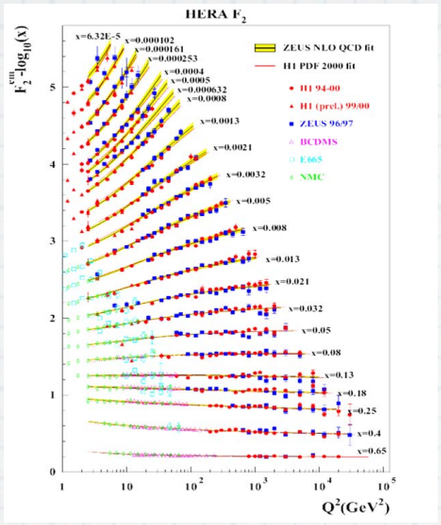
parton transverse momentum



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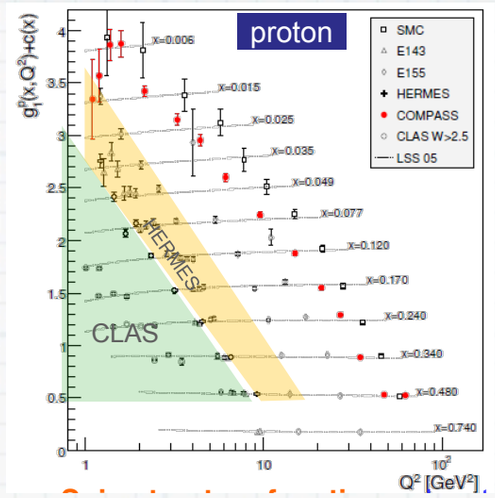
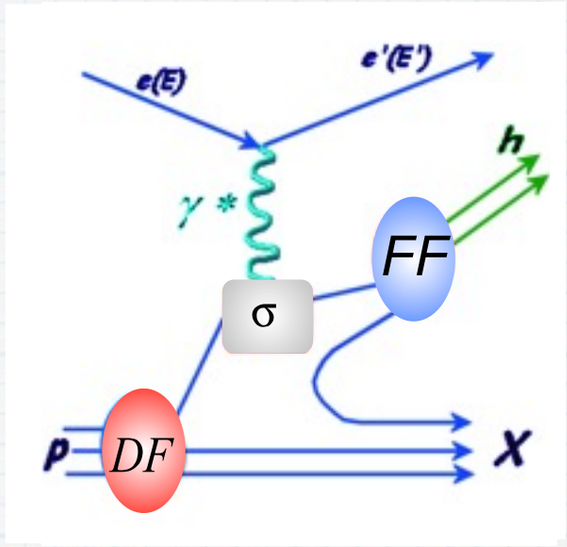




nucleon	quark: U	quark: L	quark: T
U	f_1		
L		g_1	
T			h_1

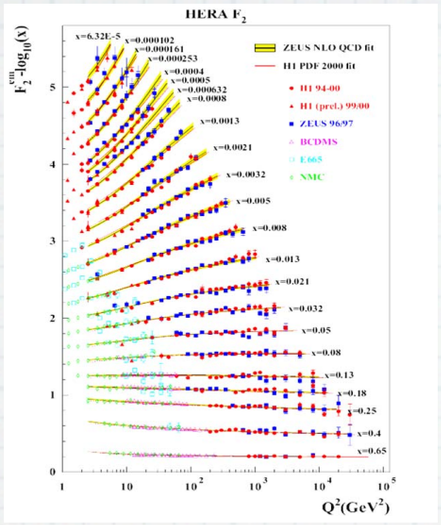
Transversity df

transverse longitudinal

nucleon spin

parton spin

parton transverse momentum



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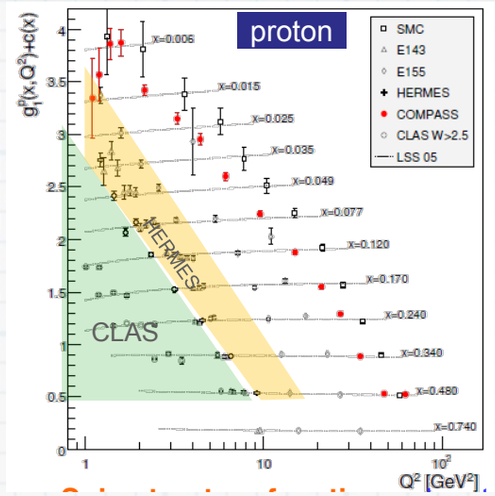
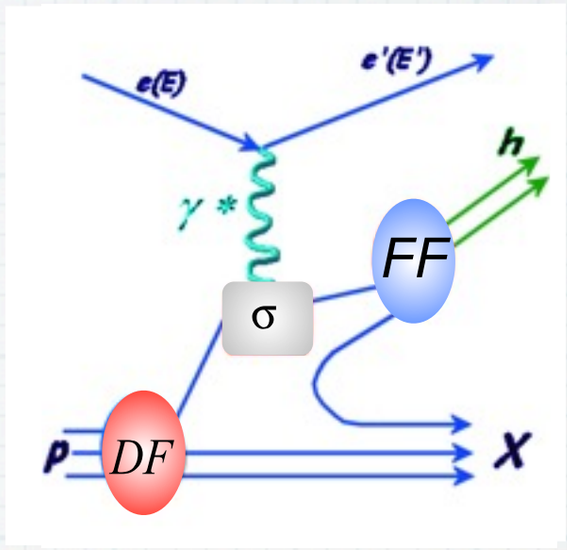
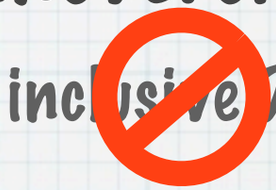




nucleon	quark: U	quark: L	quark: T
U	f_1		
L		g_1	
T			h_1

Transversity df



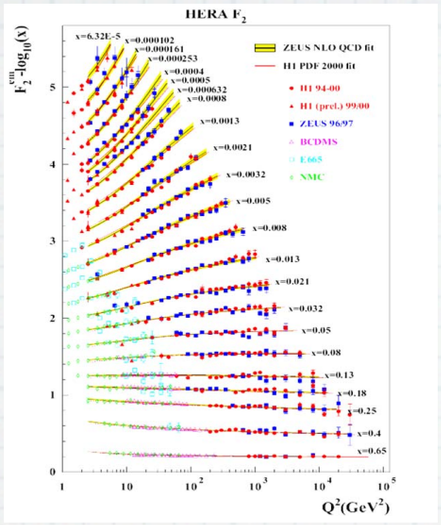
inclusive DIS

transverse longitudinal

nucleon spin

parton spin

parton transverse momentum



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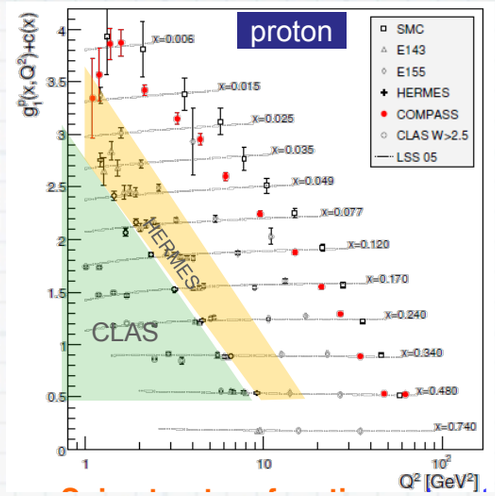
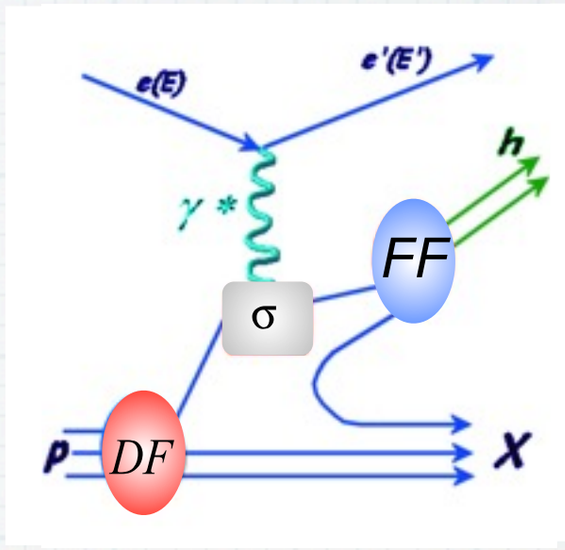




nucleon \ quark	U	L	T
U	f_1		
L		g_1	
T			h_1

chiral odd

Transversity df

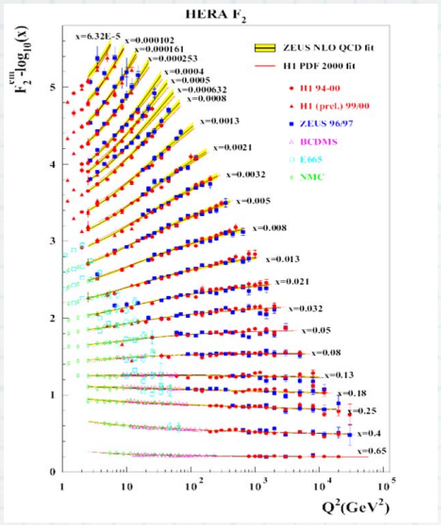
inclusive DIS

transverse longitudinal

nucleon spin

parton spin

parton transverse momentum



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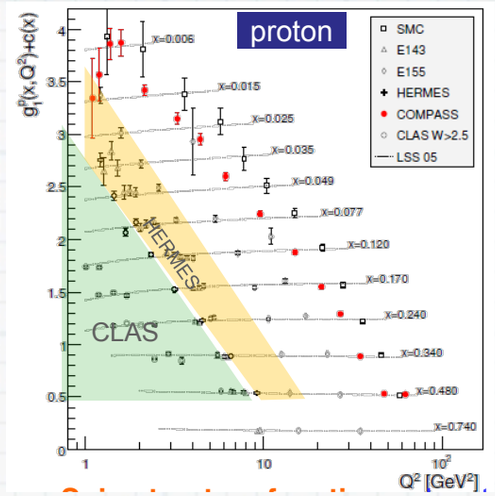
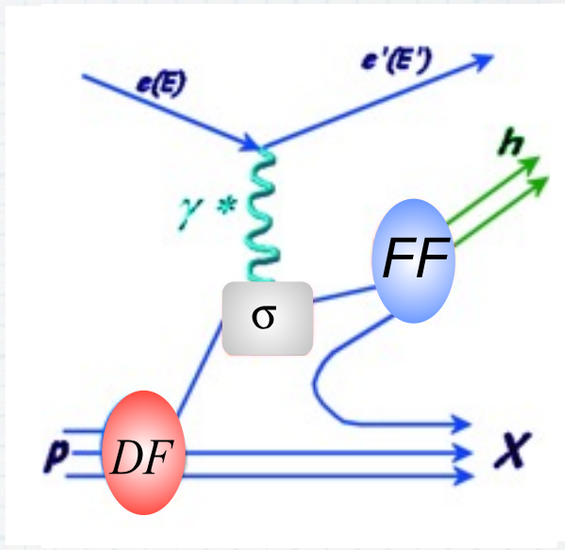




		quark		
		U	L	T
nucleon	U	f_1 ⊙		
	L		g_1 ⊙ − ⊗	
	T			h_1 → − →

chiral odd

Transversity df

~~inclusive DIS~~

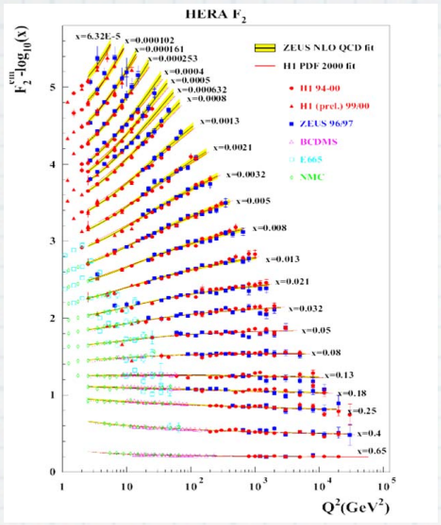
$$h_1 \otimes X$$

transverse longitudinal

nucleon spin

parton spin

parton transverse momentum



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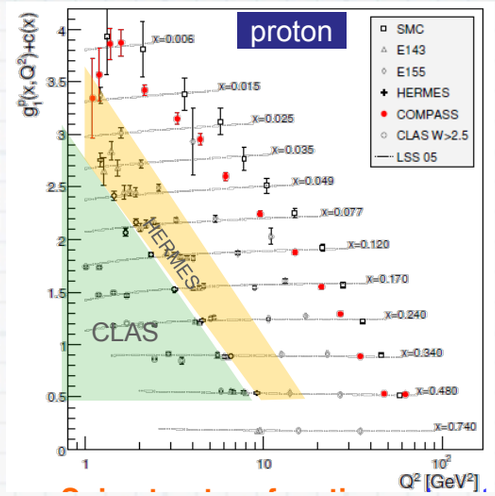
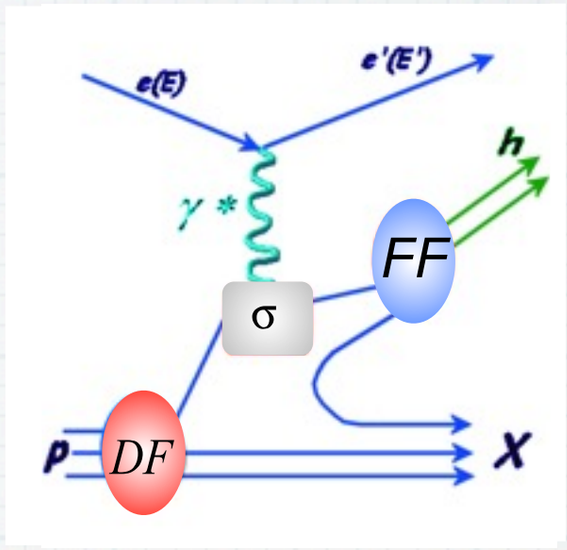




nucleon \ quark	U	L	T
U	f_1		
L		g_1	
T			h_1

chiral odd

Transversity df

~~inclusive DIS~~

$$h_1 \otimes X$$

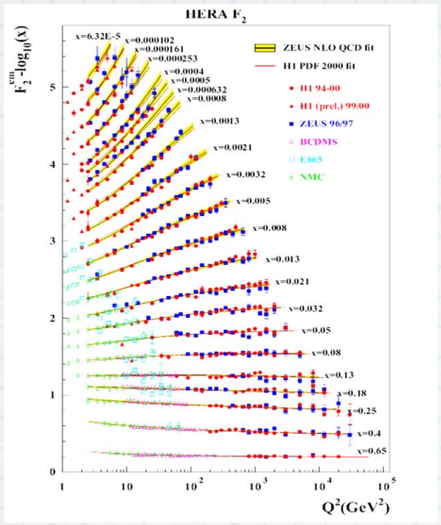
chiral odd chiral odd

transverse longitudinal

nucleon spin

parton spin

parton transverse momentum



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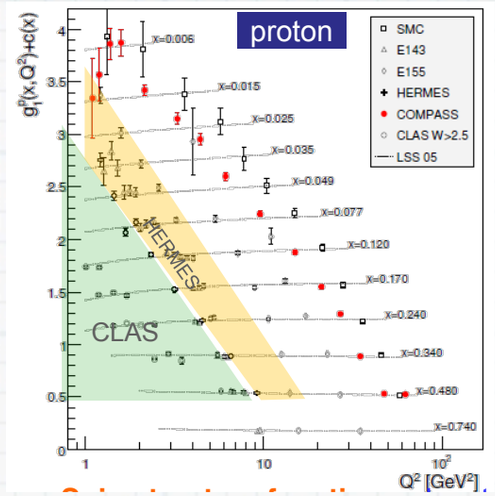
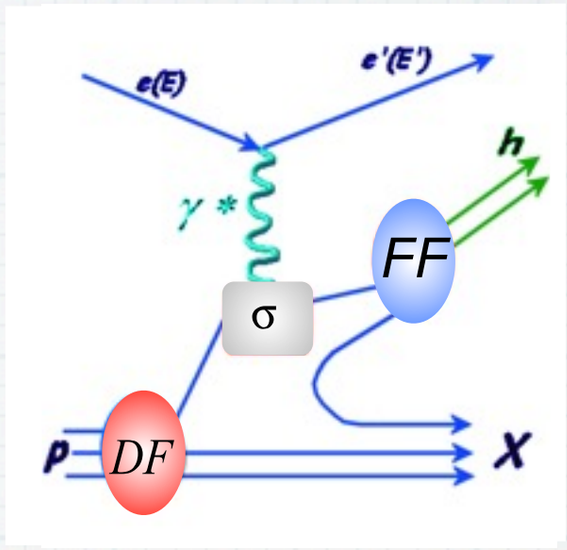




nucleon	quark: U	quark: L	quark: T
U	f_1		
L		g_1	
T			h_1

chiral odd

Transversity df

inclusive DIS

$$h_1 \otimes X$$

chiral odd chiral odd

chiral even

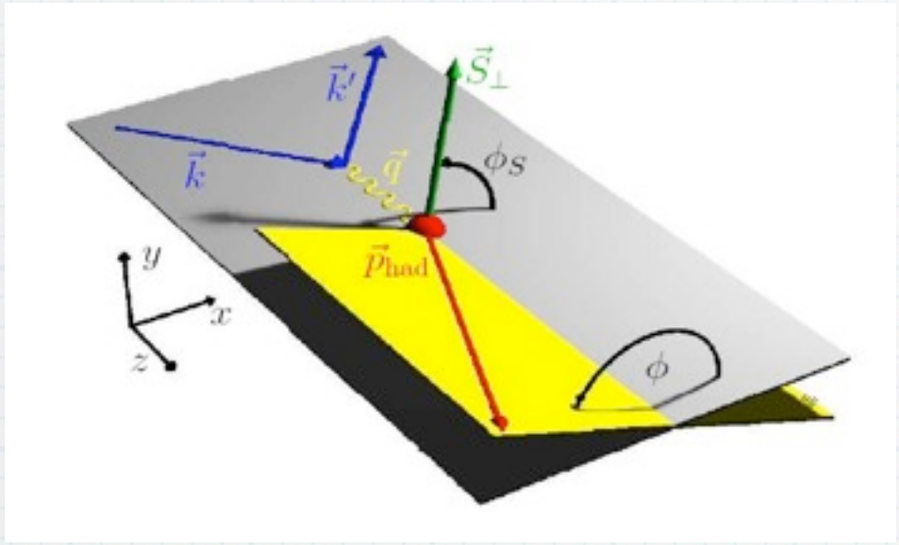
transverse longitudinal

nucleon spin

parton spin

parton transverse momentum

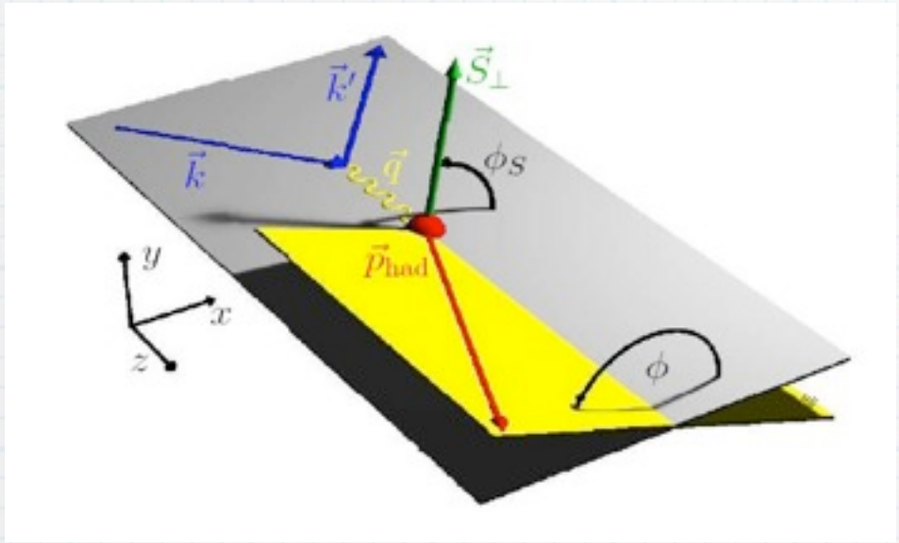
1-hadron production



$$A_{UT} \propto h_1 \otimes H_1^\perp$$

Transversity in DIS

1-hadron production

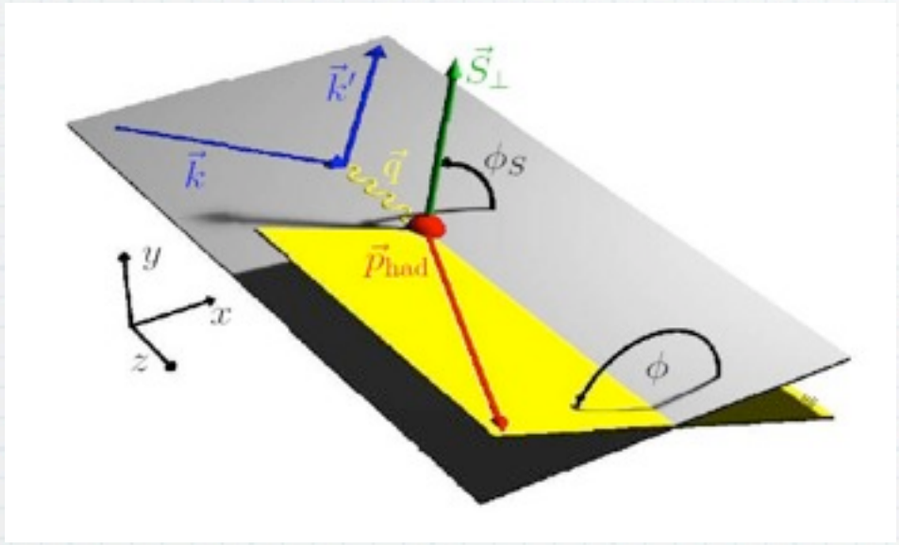


$$A_{UT} \propto h_1 \otimes H_1^\perp$$

Collins ff

Transversity in DIS

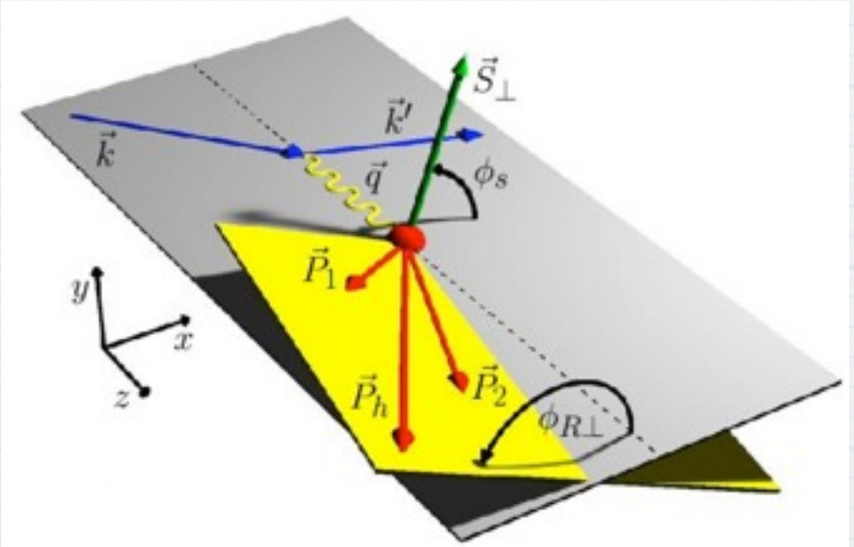
1-hadron production



$$A_{UT} \propto h_1 \otimes H_1^\perp$$

Collins ff

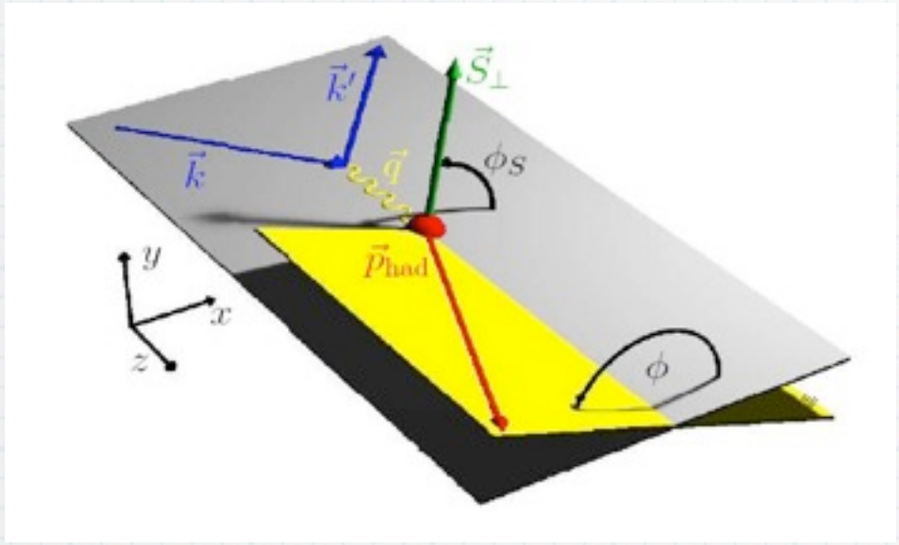
2-hadron production



$$A_{UT} \propto h_1 \times H_1^\sphericalangle$$

Transversity in DIS

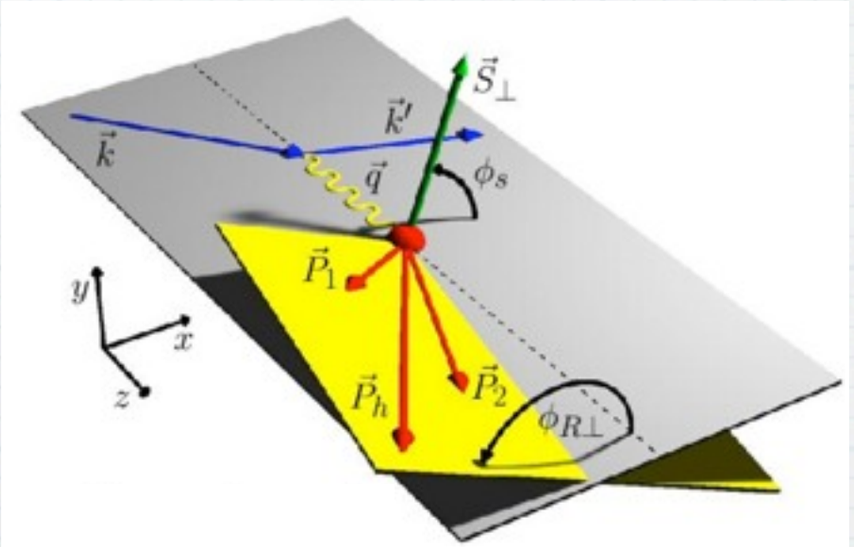
1-hadron production



$$A_{UT} \propto h_1 \otimes H_1^\perp$$

Collins ff

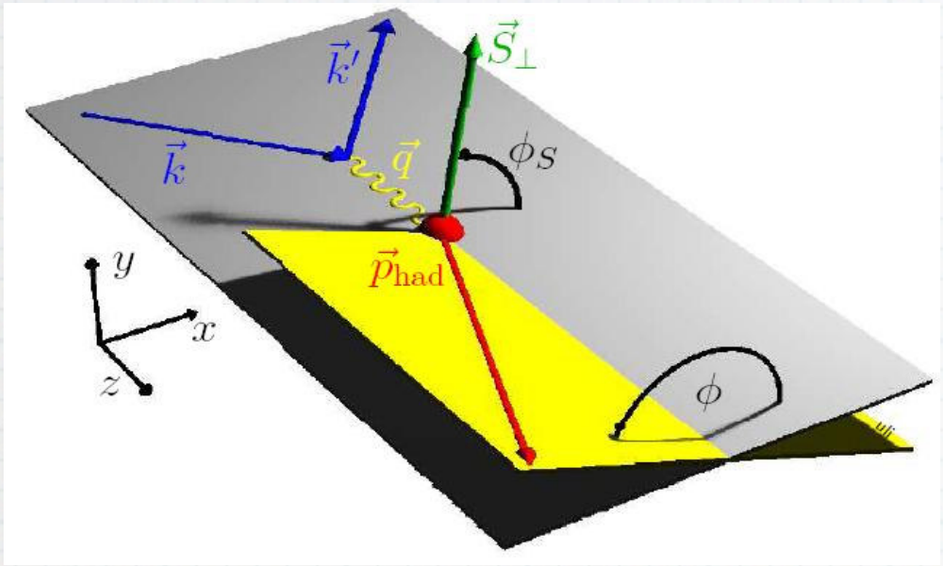
2-hadron production



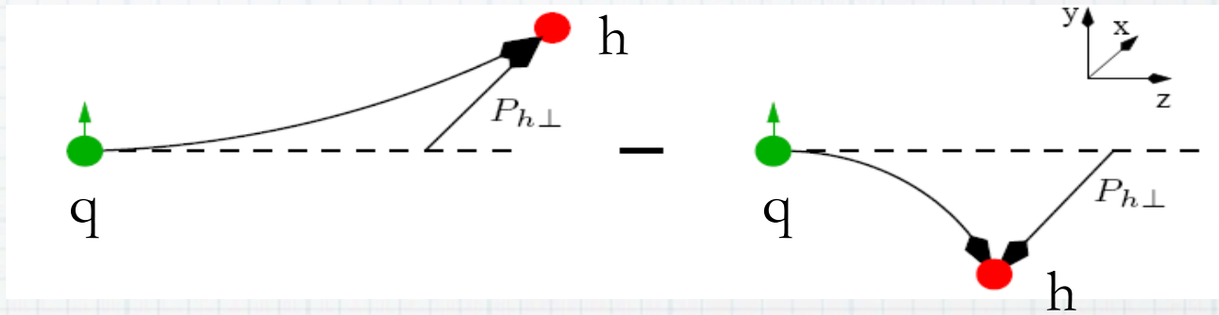
$$A_{UT} \propto h_1 \times H_1^\sphericalangle$$

Interference ff

Transversity in DIS

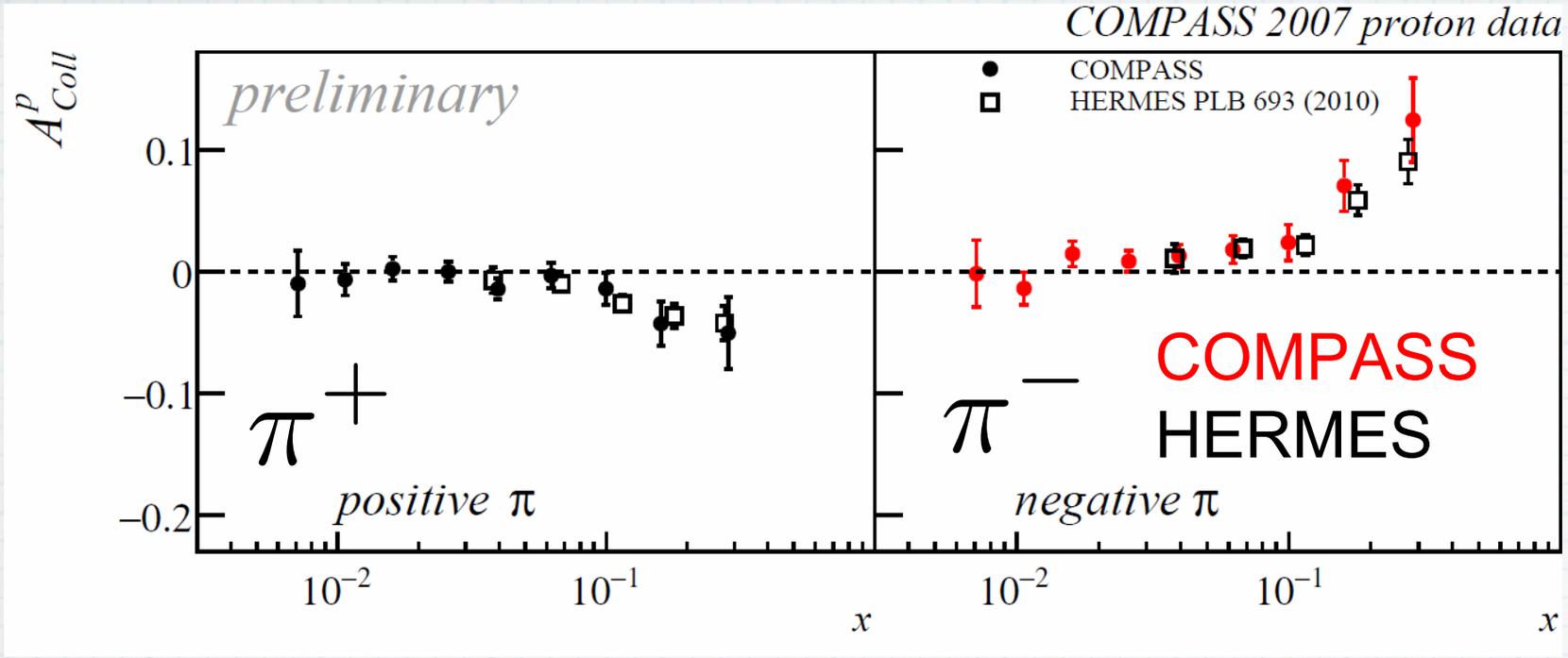


$$A_{UT} \propto h_1 \otimes H_1^\perp$$

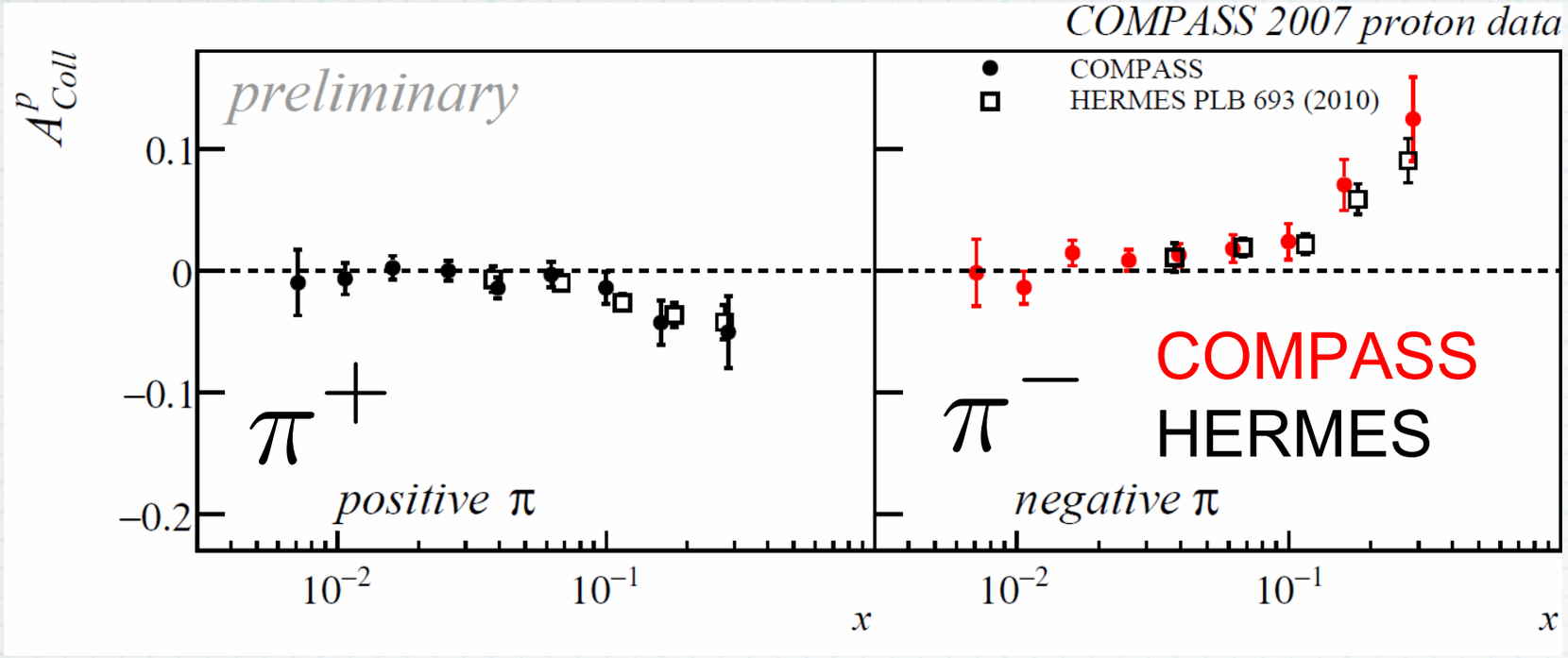


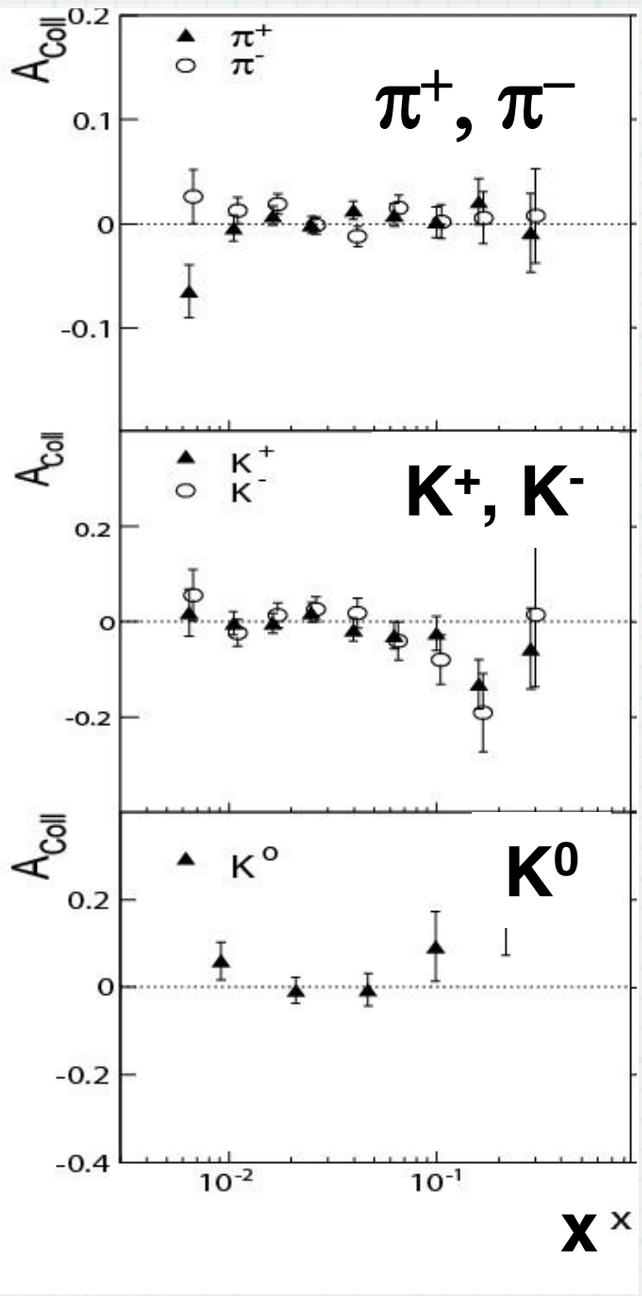
Collins mechanism: left-right asymmetry from correlations between quark transverse spin and outgoing hadron direction

1-hadron production

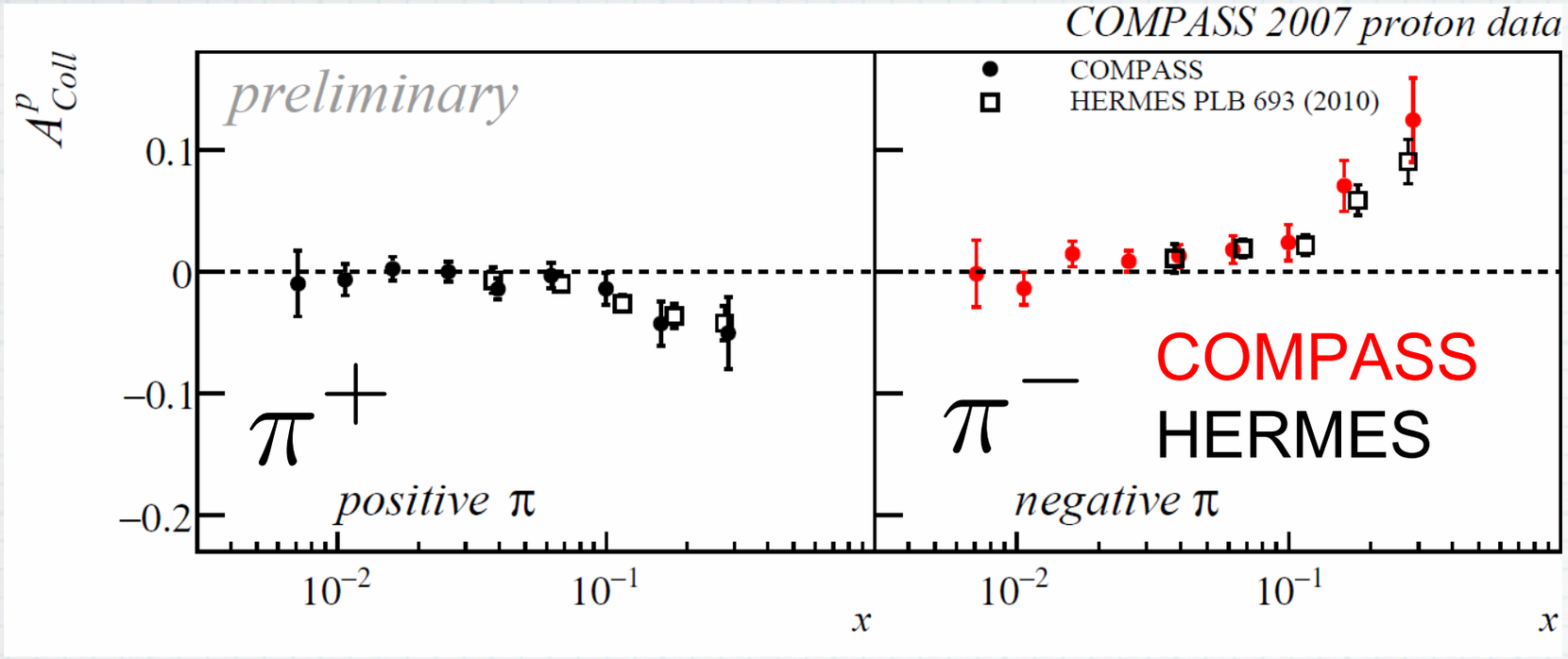


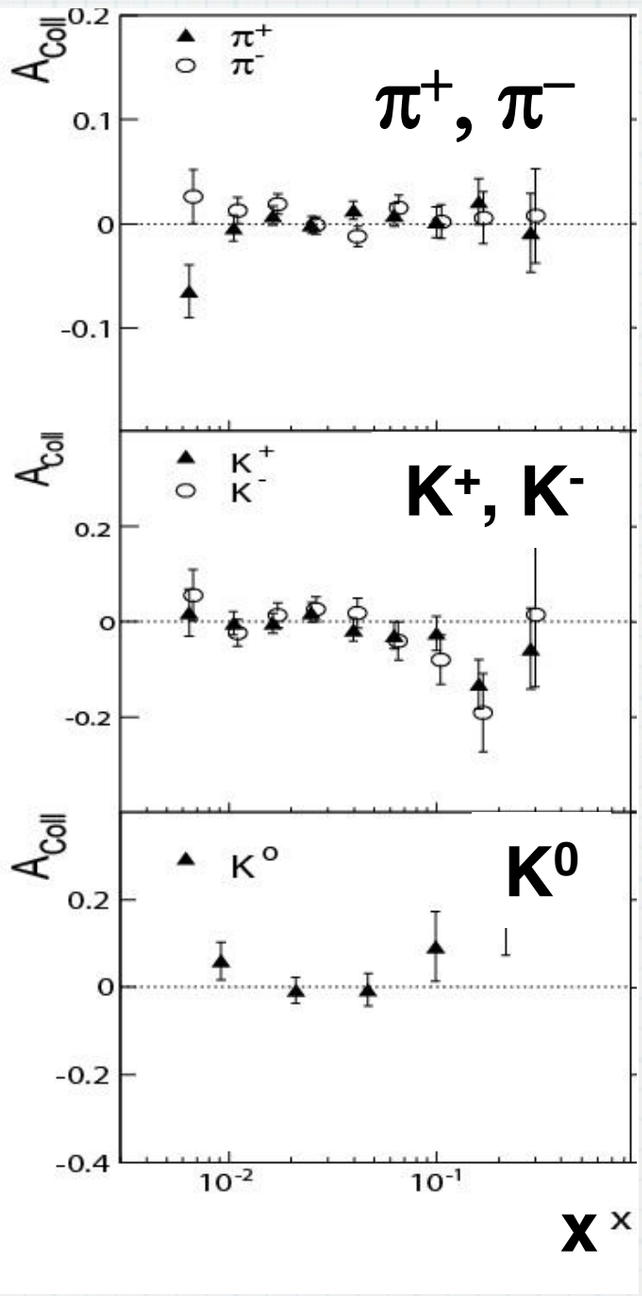
1-hadron production





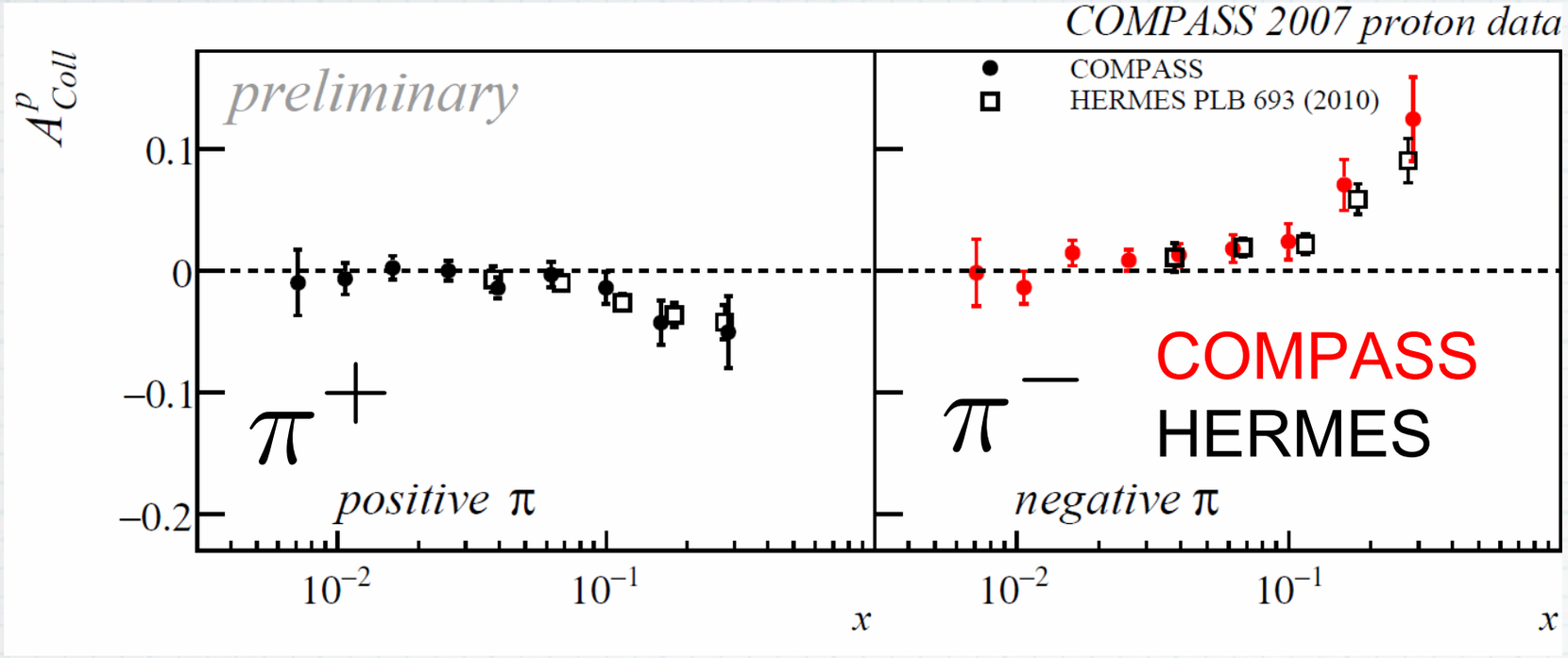
1-hadron production

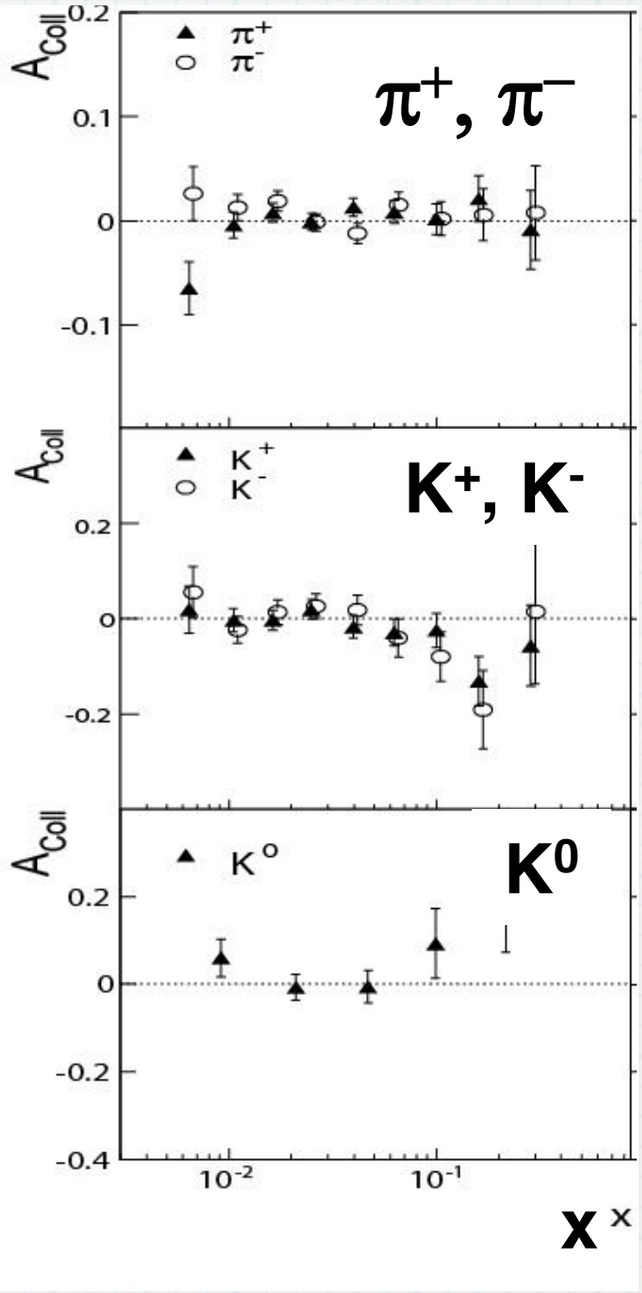




$$A_{UT} \propto h_1 \otimes H_1^{\perp}$$

1-hadron production





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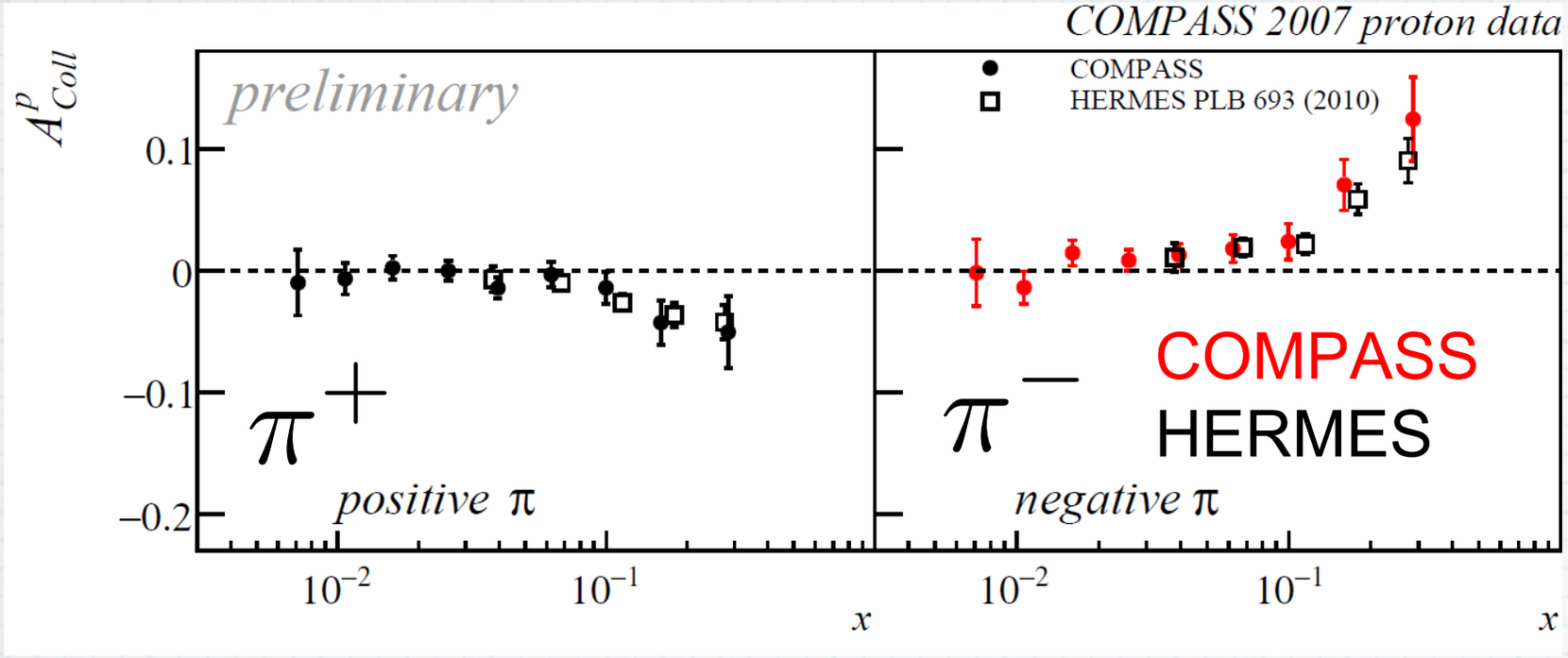
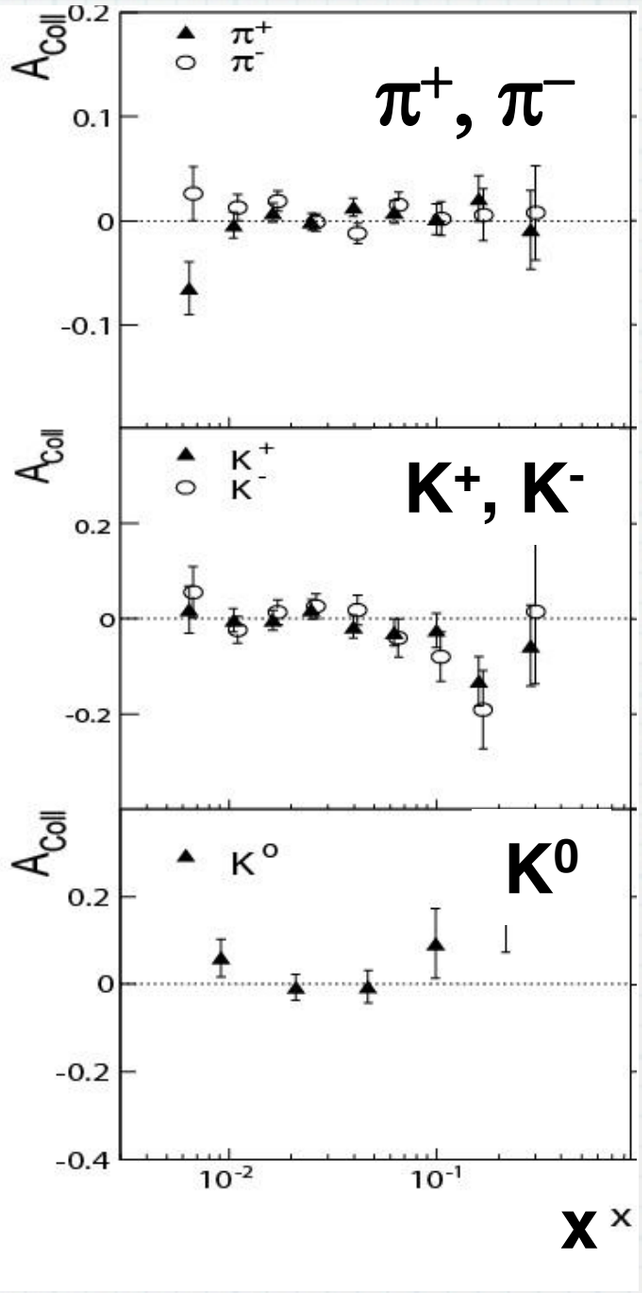
1-hadron production





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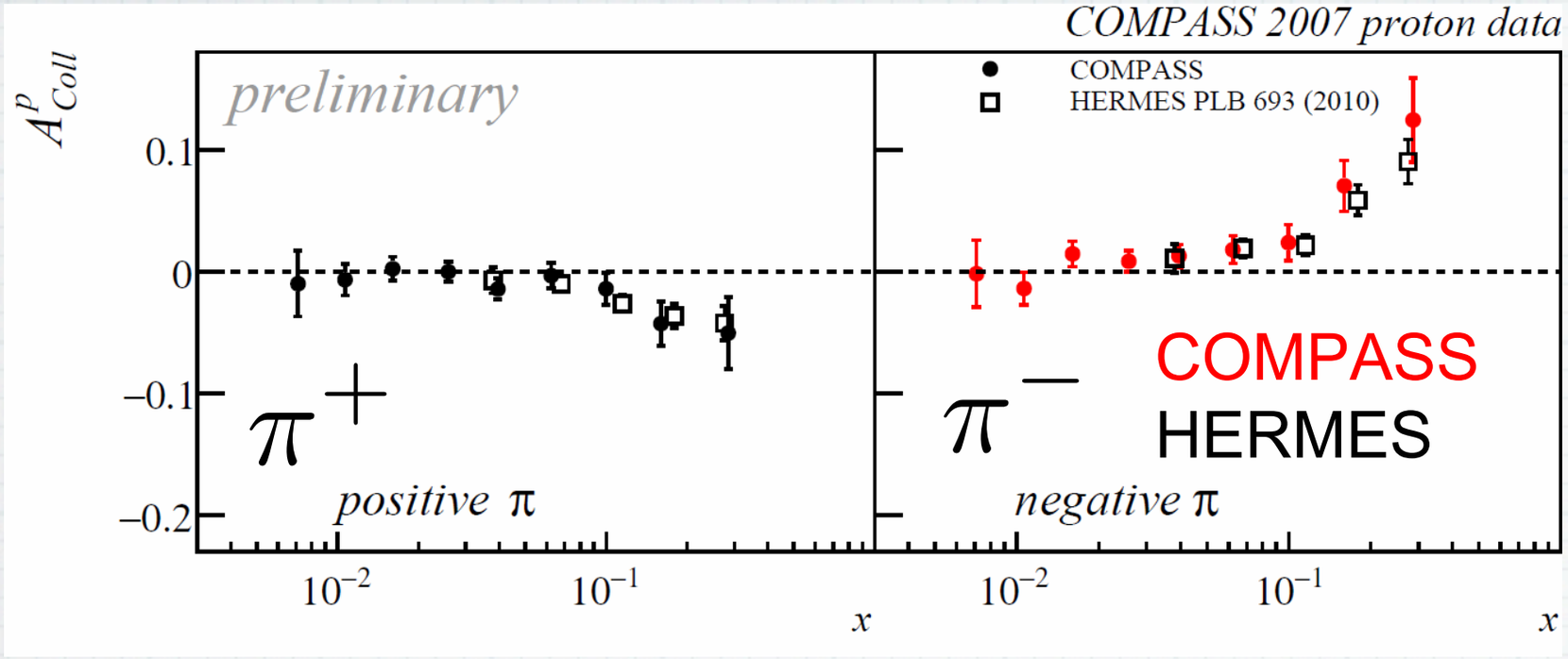
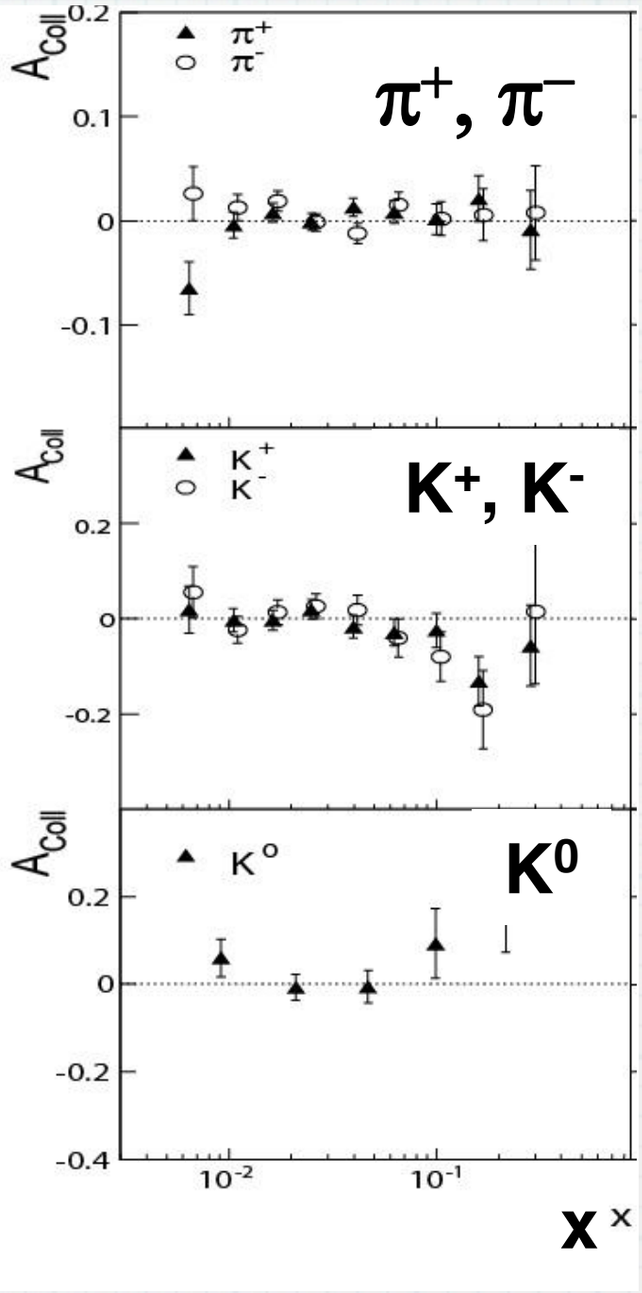
1-hadron production



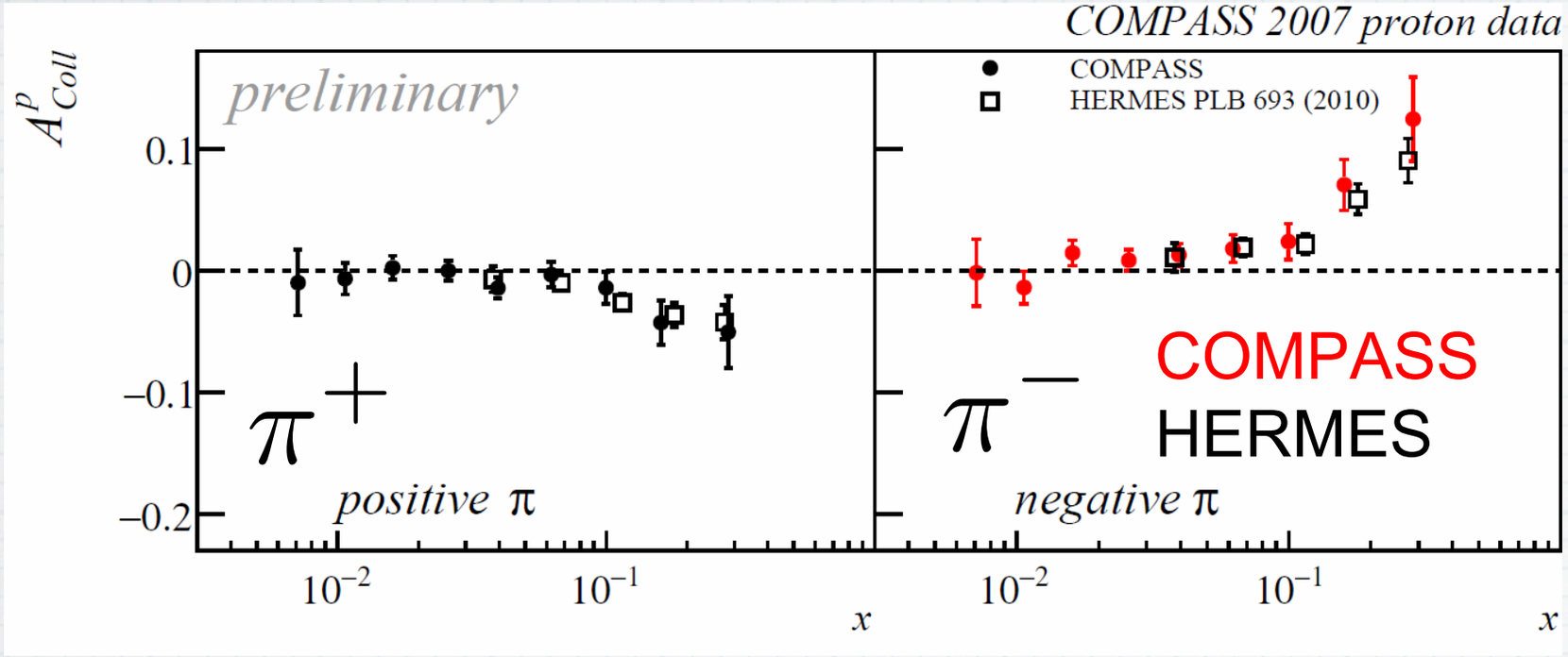


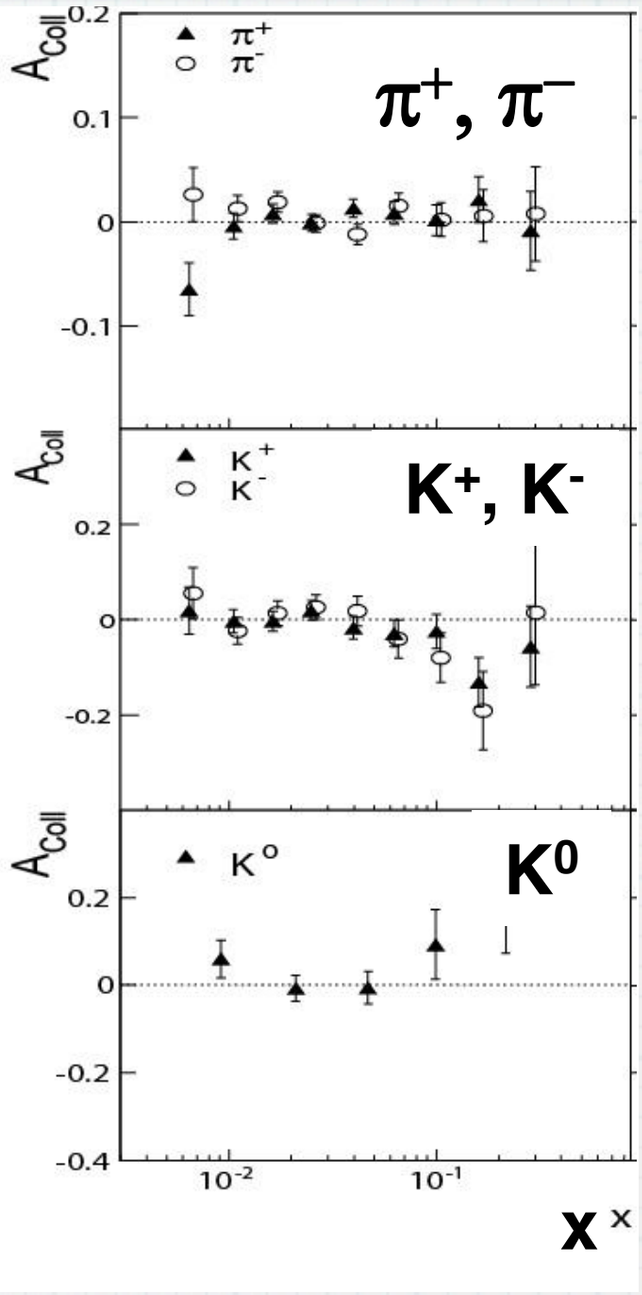
convolution over quark transverse momenta

$$A_{UT} \propto h_1 \otimes H_1^{\perp}$$

hermes COMPASS BELLE

1-hadron production



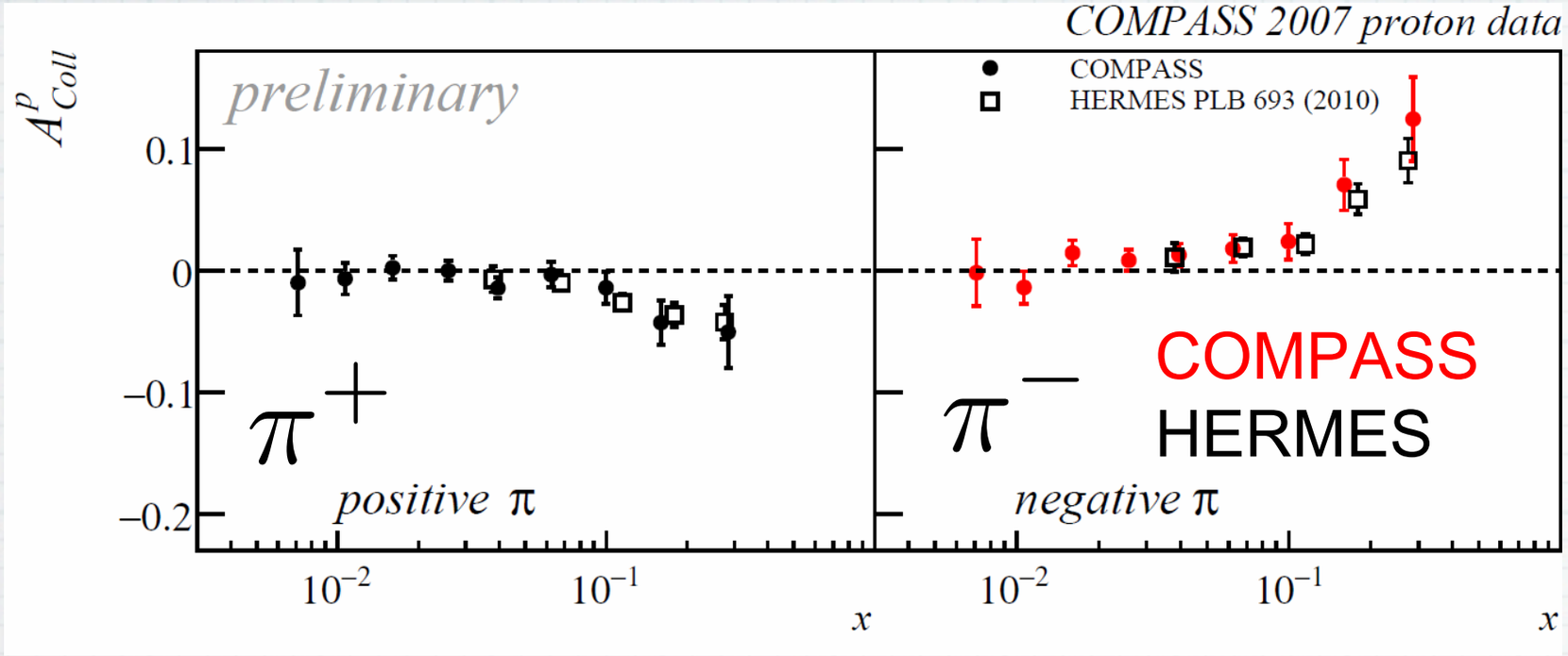


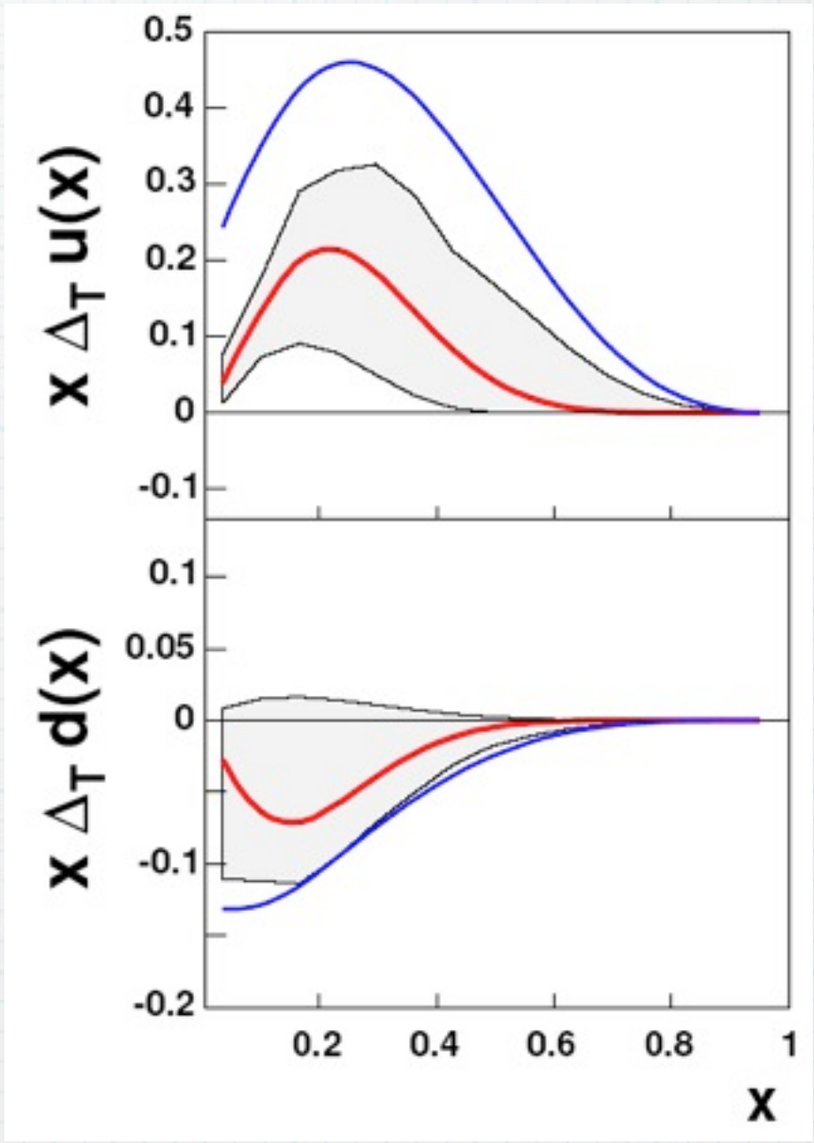
Gaussian ansatz

$$A_{UT} \propto h_1 \otimes H_1^{\perp}$$

hermes COMPASS BELLE

1-hadron production



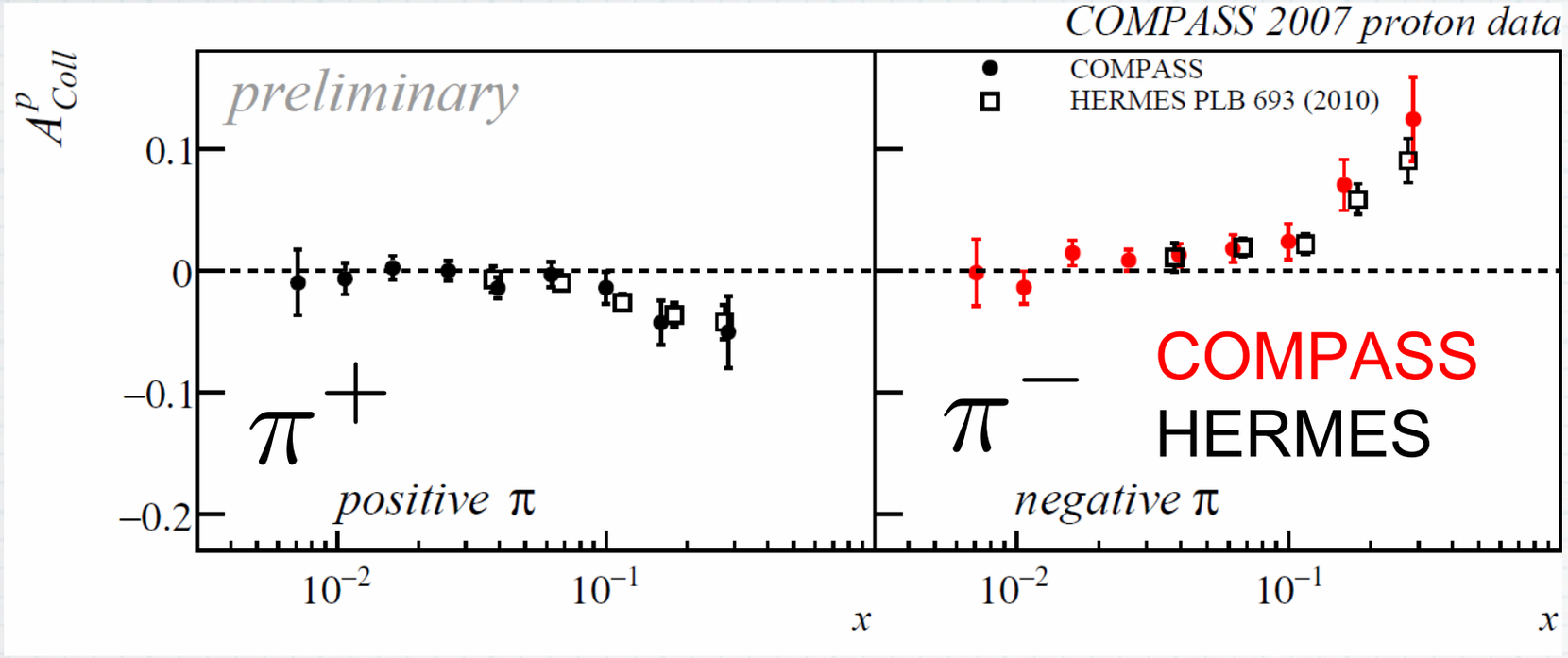


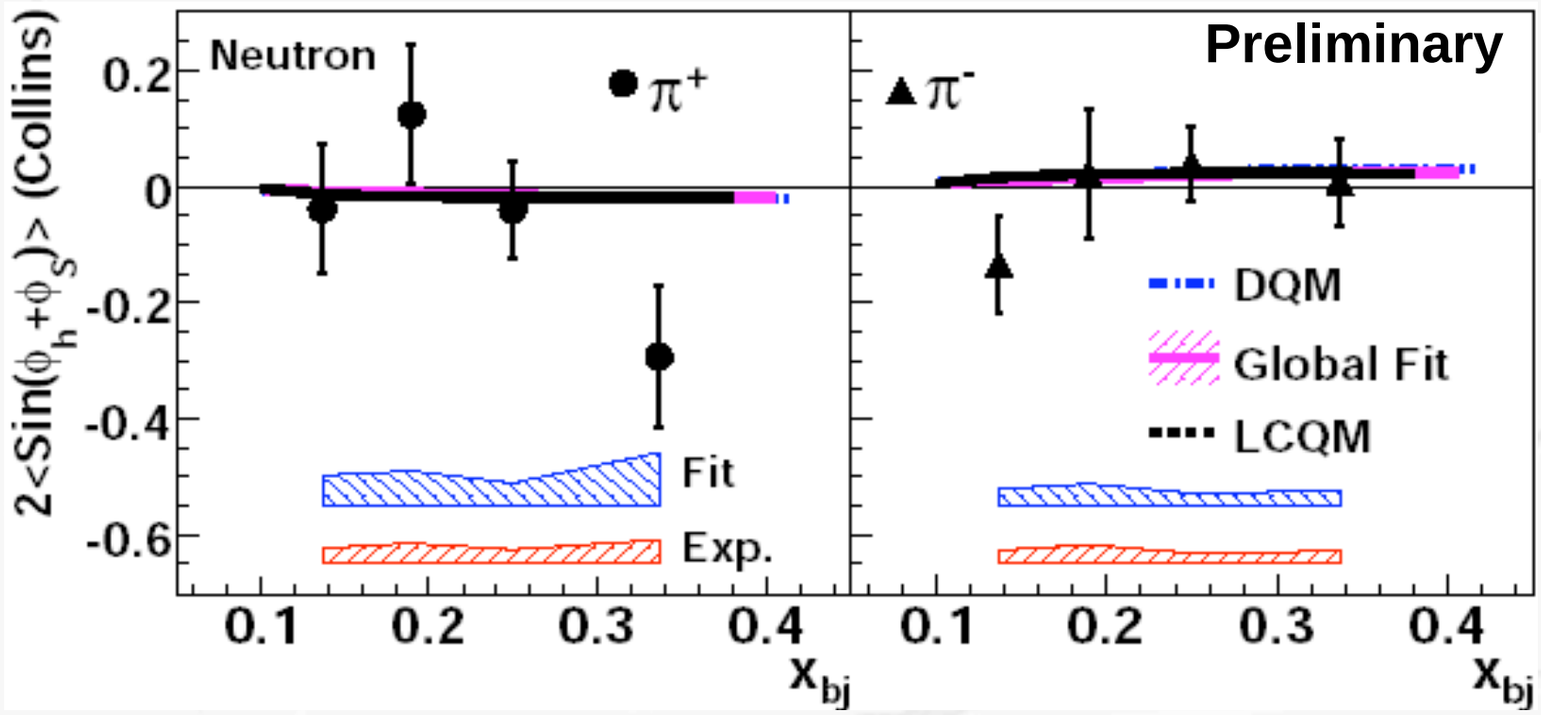
Gaussian ansatz

$$A_{UT} \propto h_1 \otimes H_1^{\perp}$$

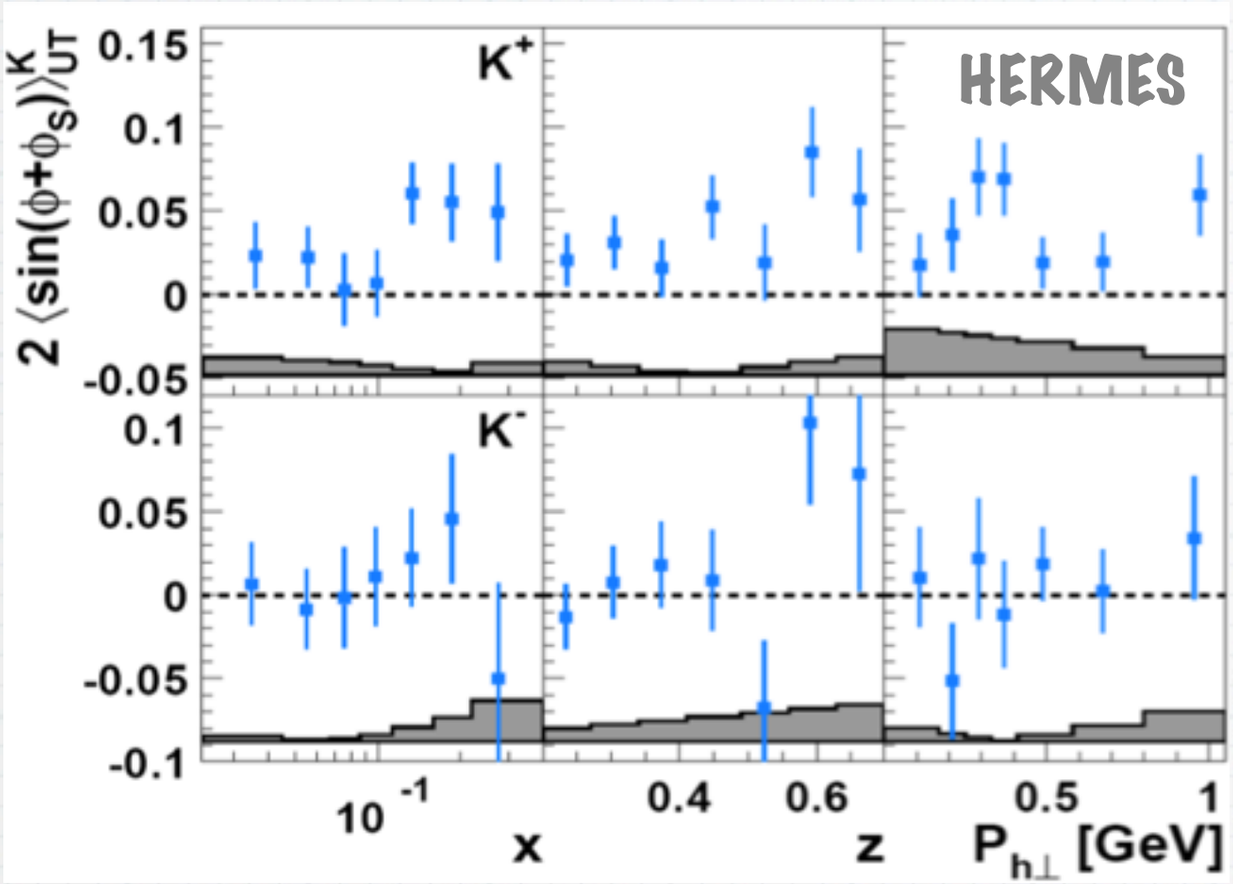
hermes COMPASS BELLE

1-hadron production

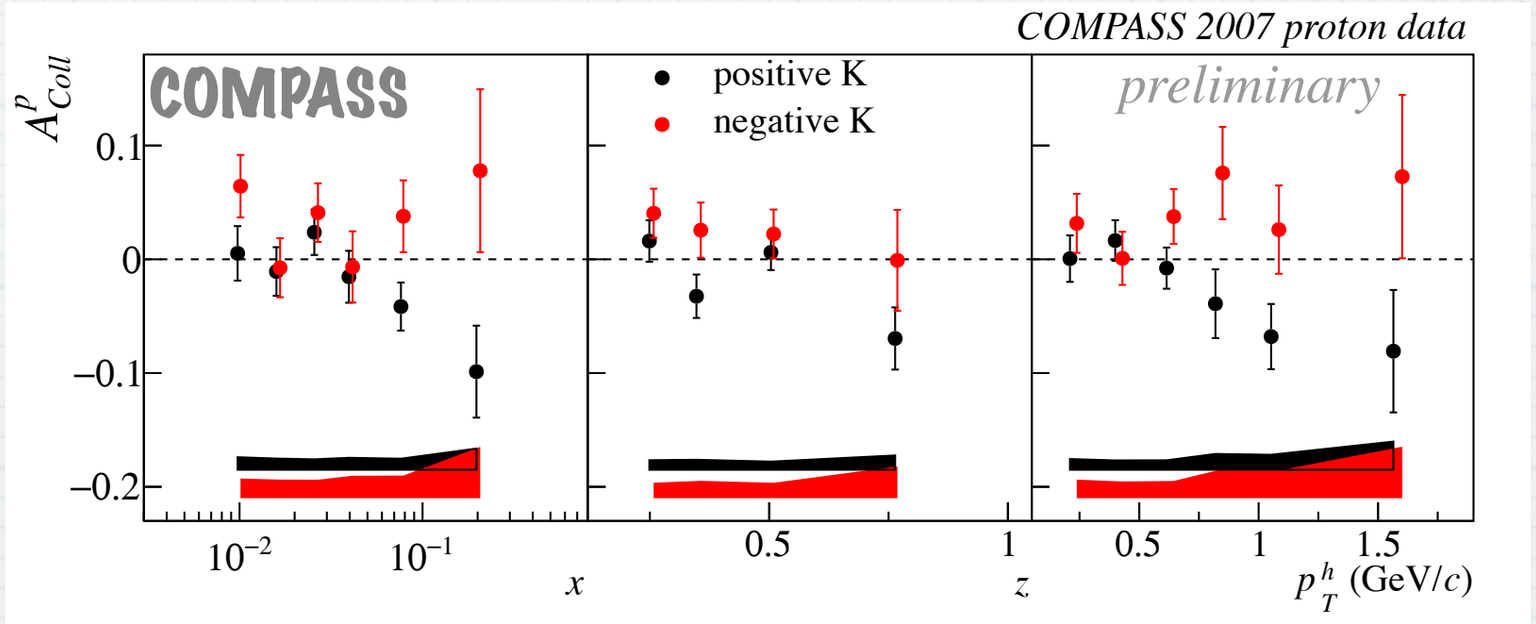




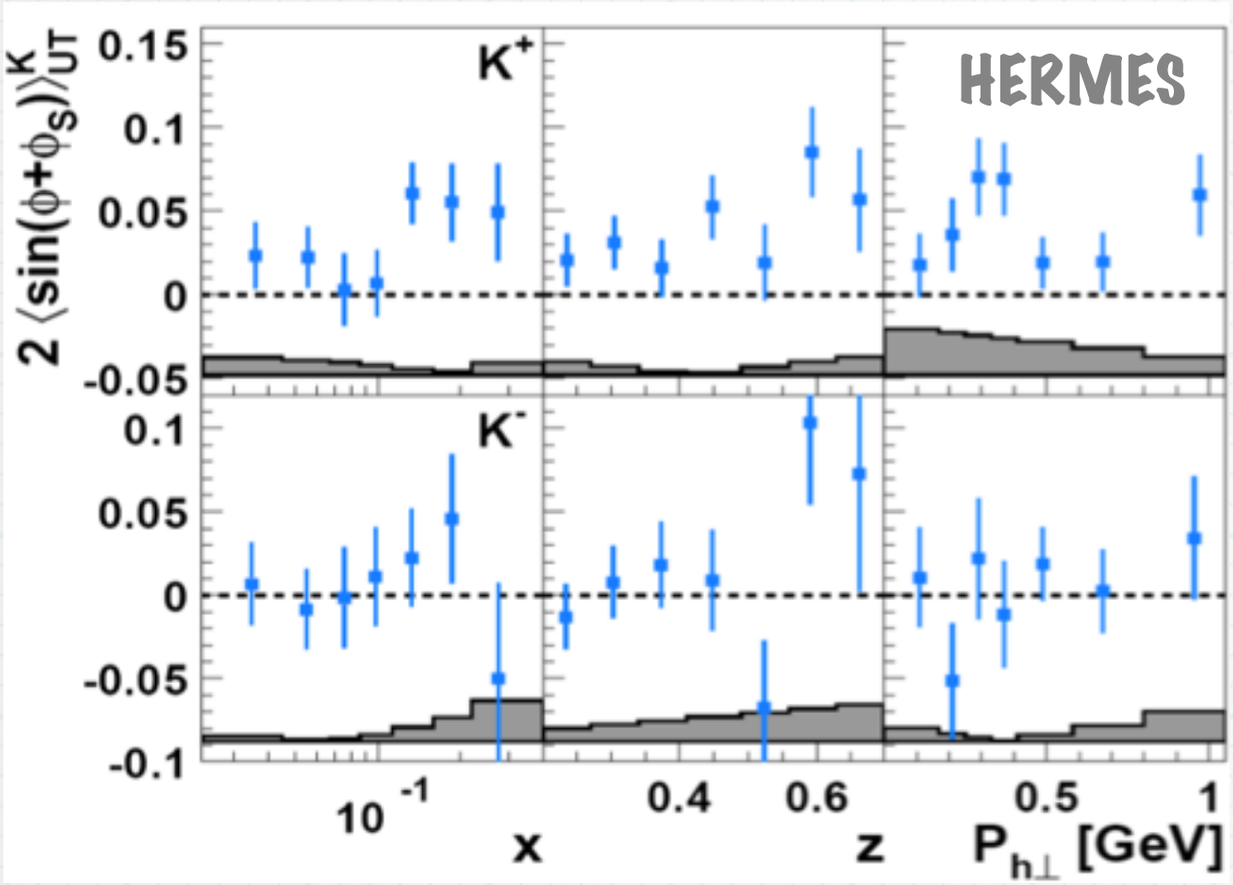
1-hadron production

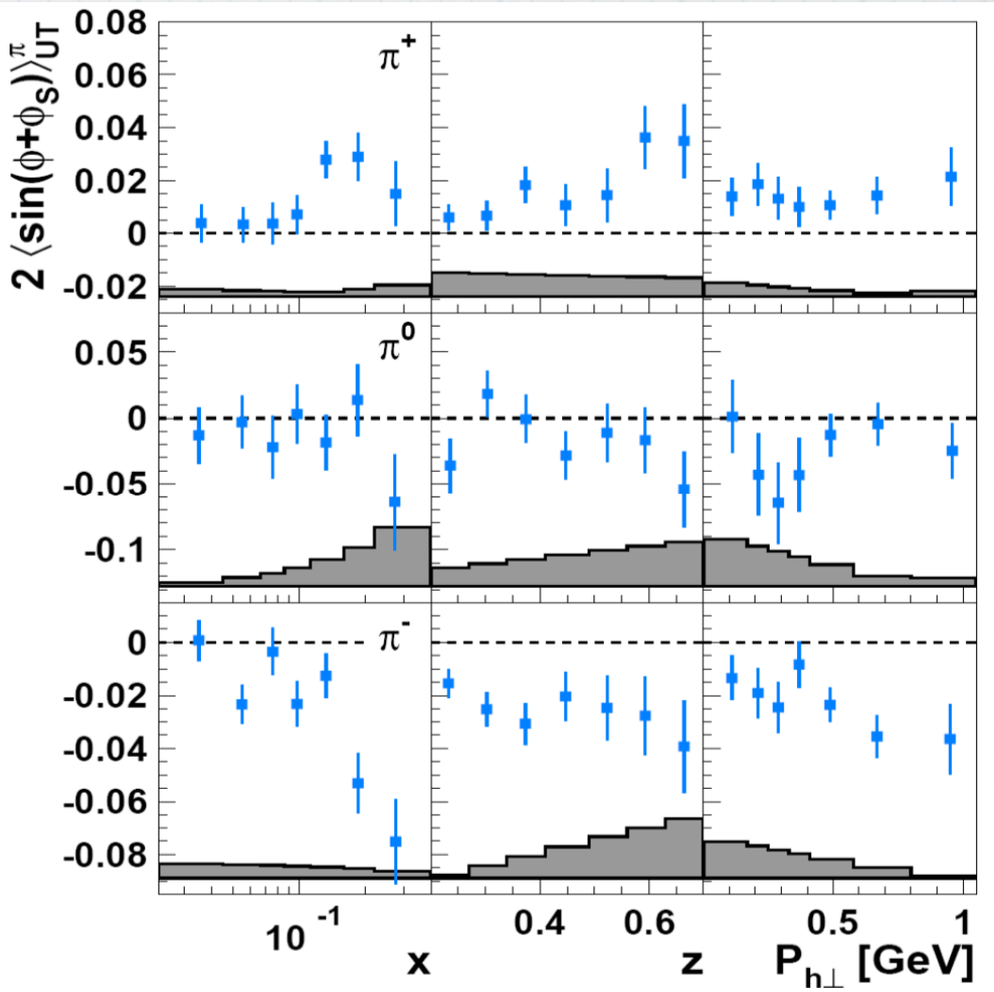


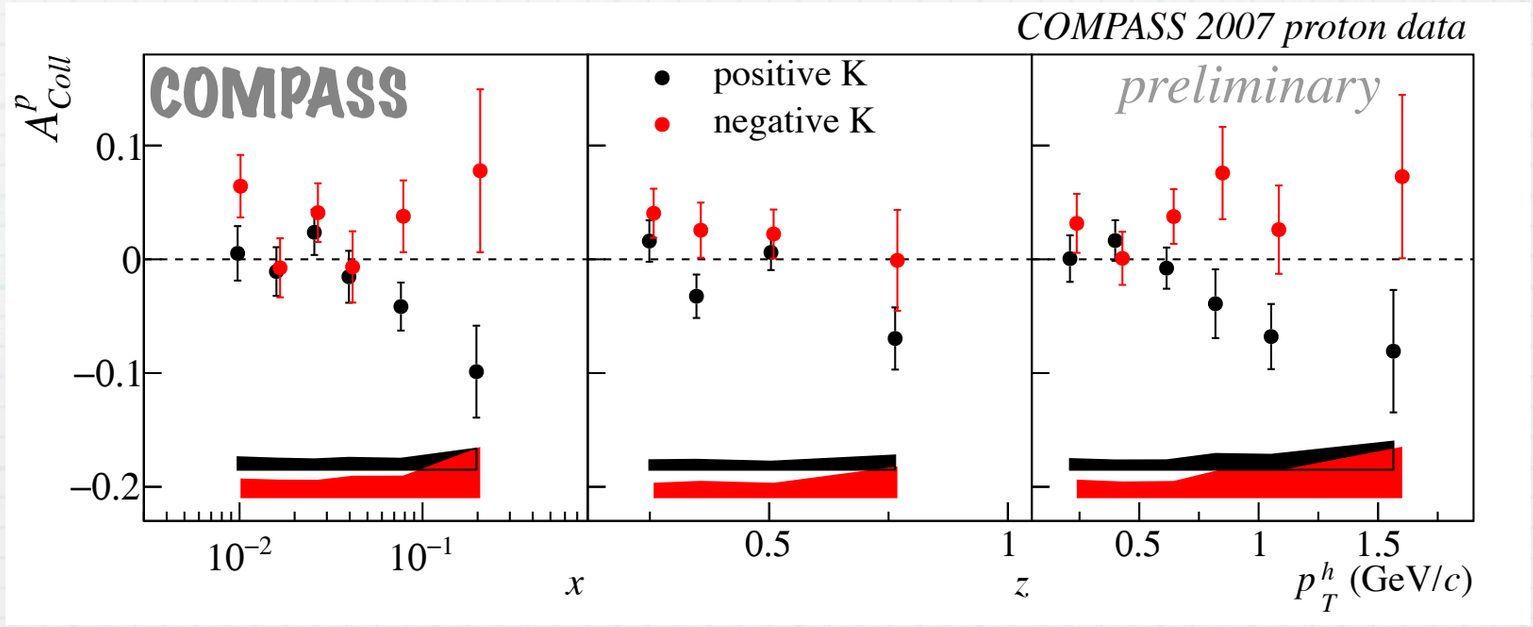
(different sign convention)



1-hadron production







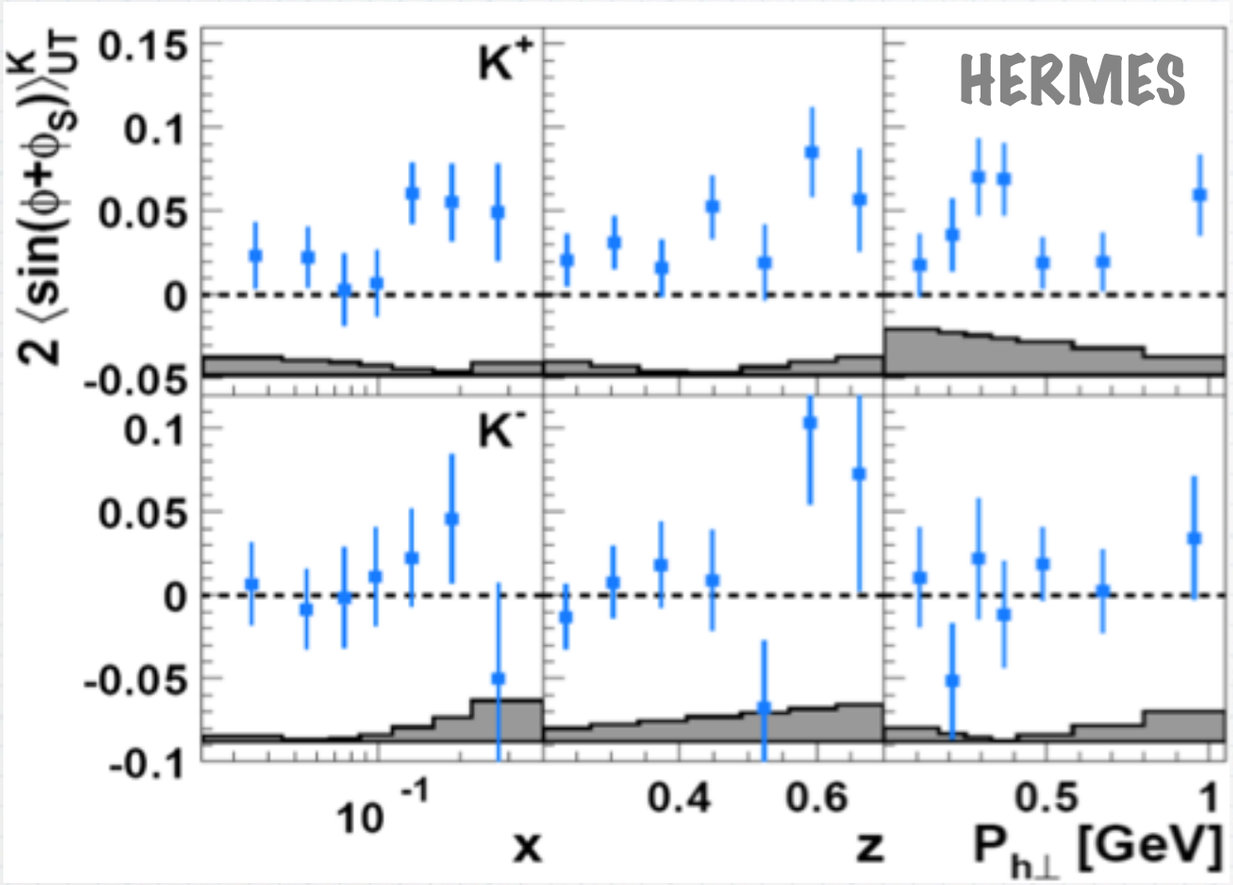
(different sign convention)

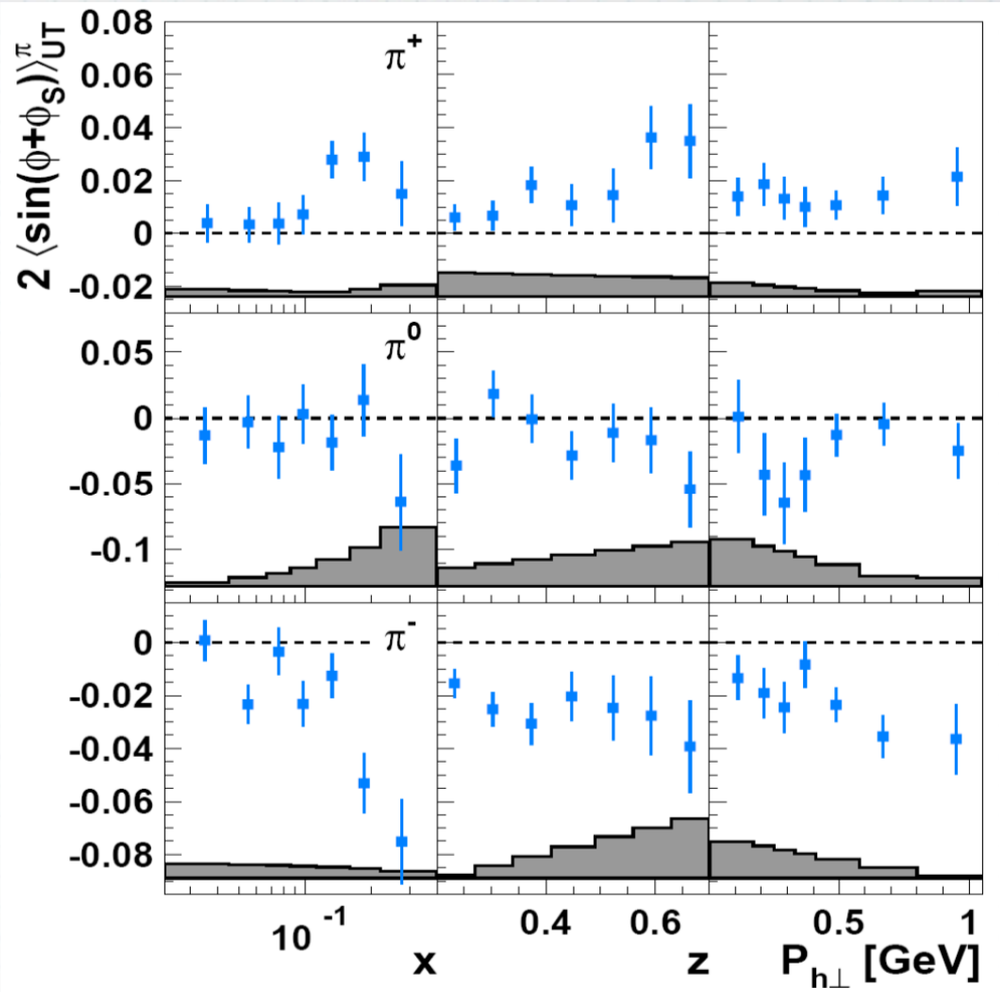
1-hadron production

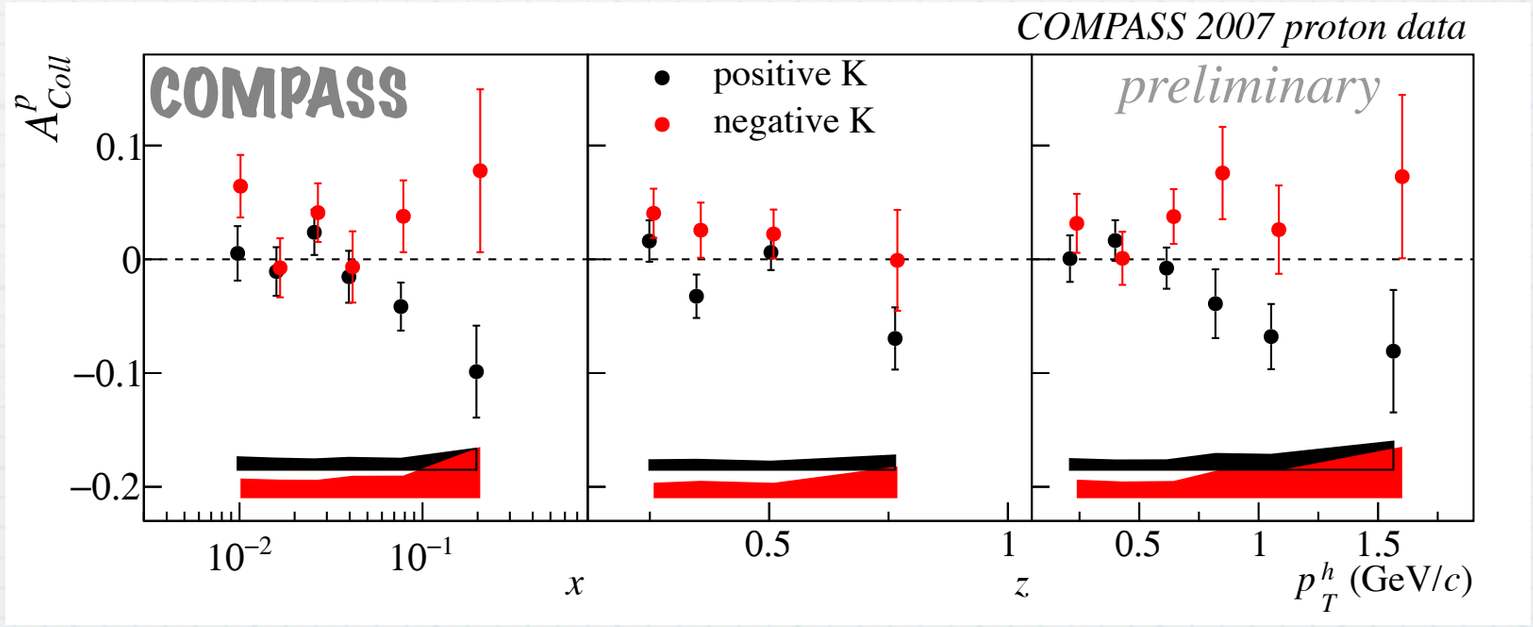
1-hadron production

Sea role?

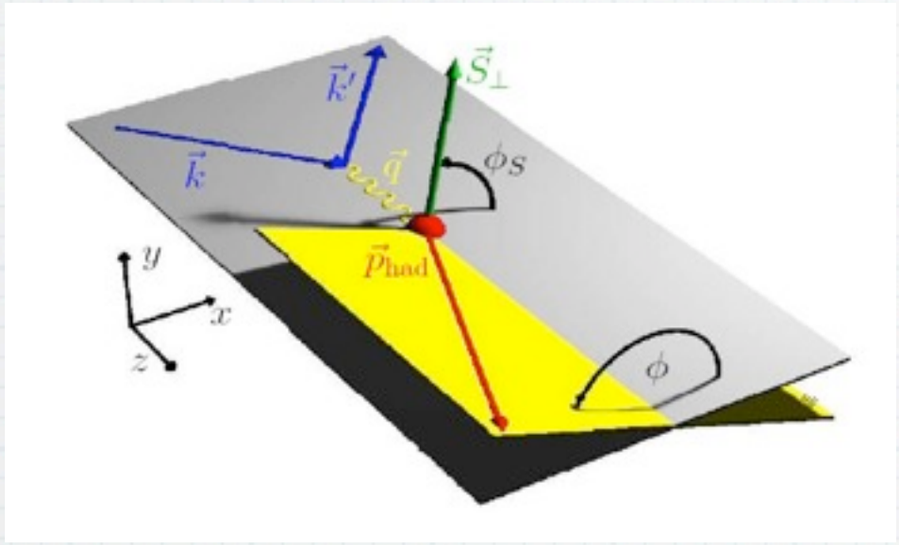
(different sign convention)







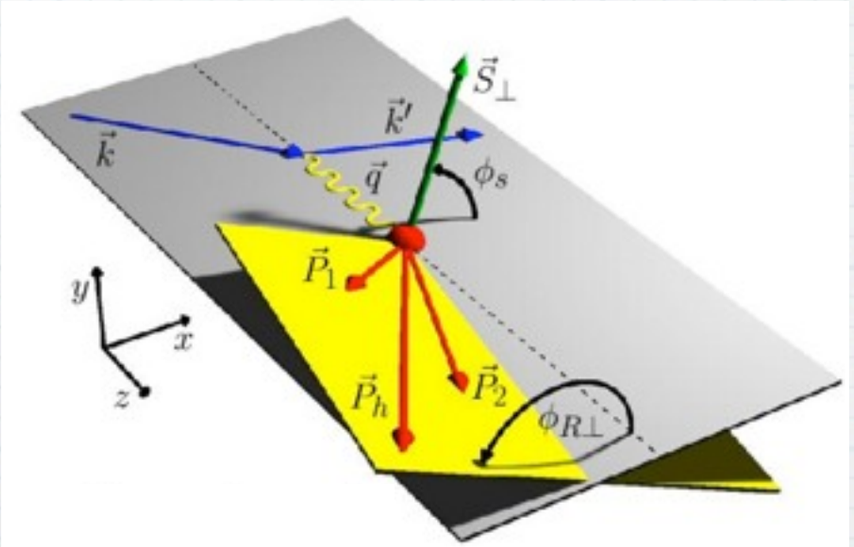
1-hadron production



$$A_{UT} \propto h_1 \otimes H_1^\perp$$

Collins ff

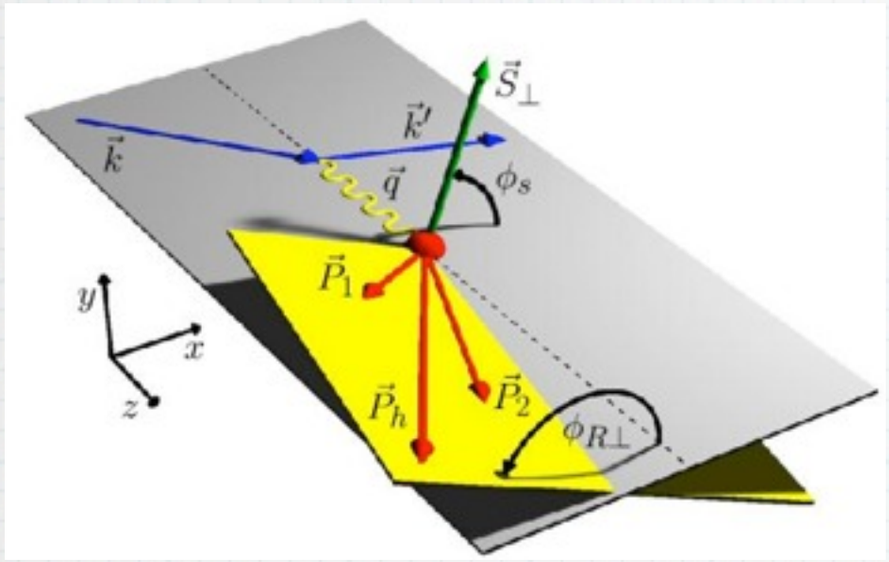
2-hadron production



$$A_{UT} \propto h_1 \times H_1^\sphericalangle$$

Interference ff

Transversity in DIS



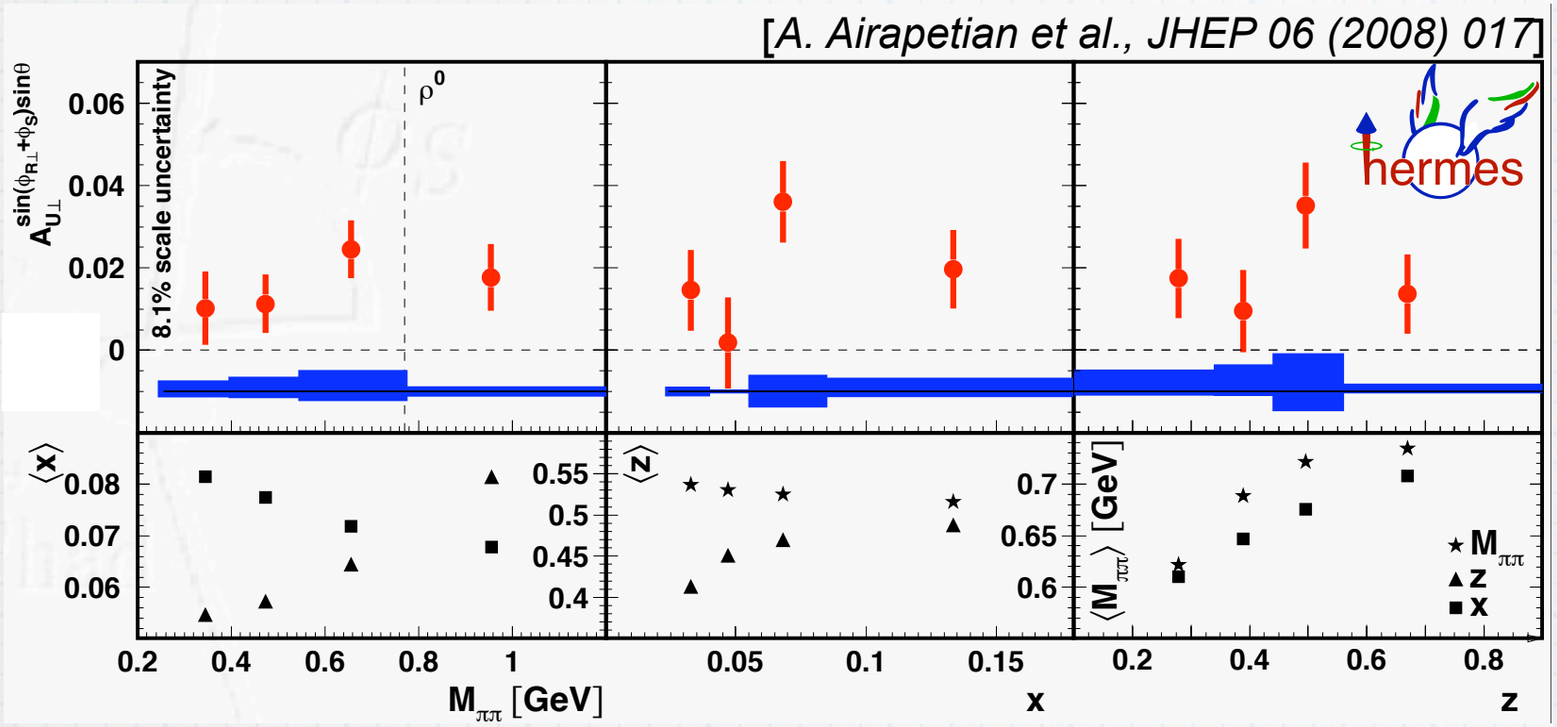
$$A_{UT} \propto h_1 \times H_1^{\sphericalangle}$$

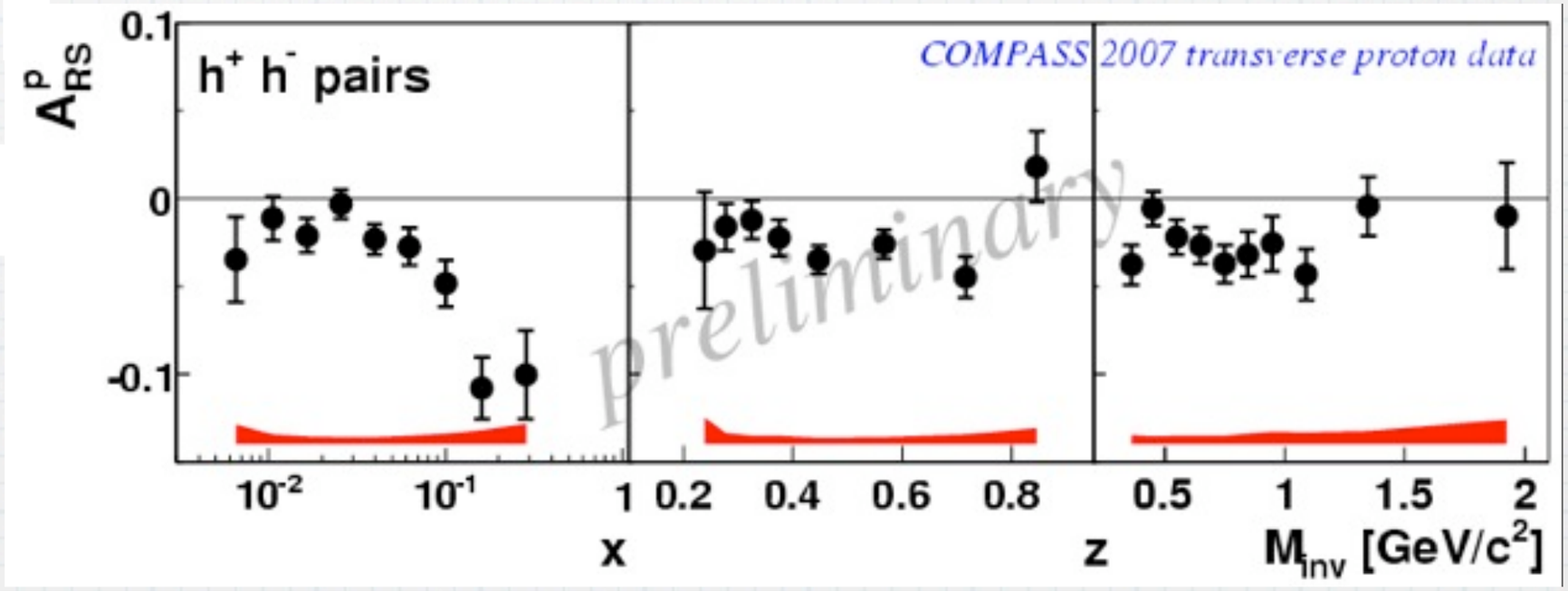
Interference Fragmentation:

left-right asymmetry from correlations between quark transverse spin and relative orbital angular momentum of the hadron pair

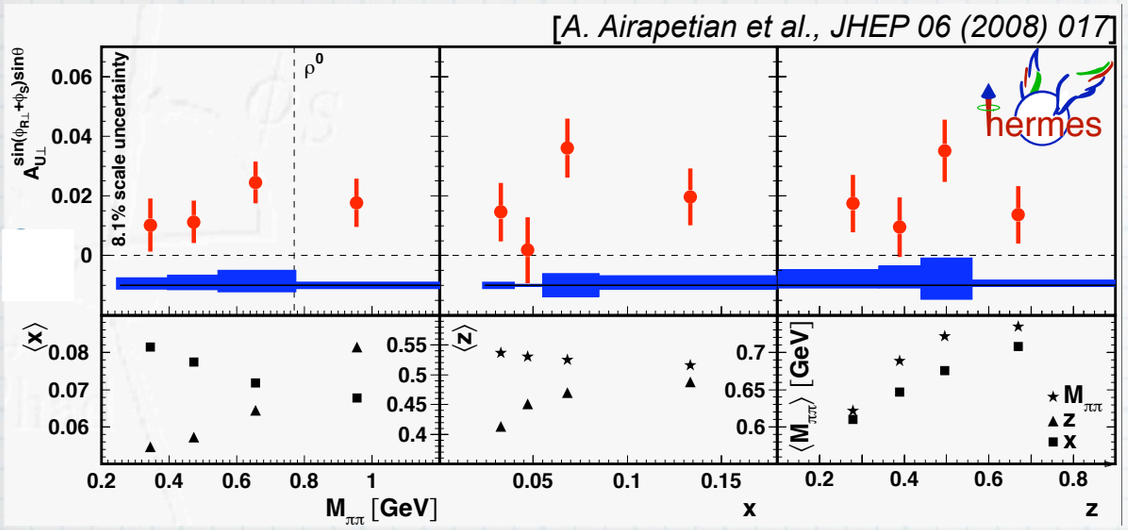
2-hadron production

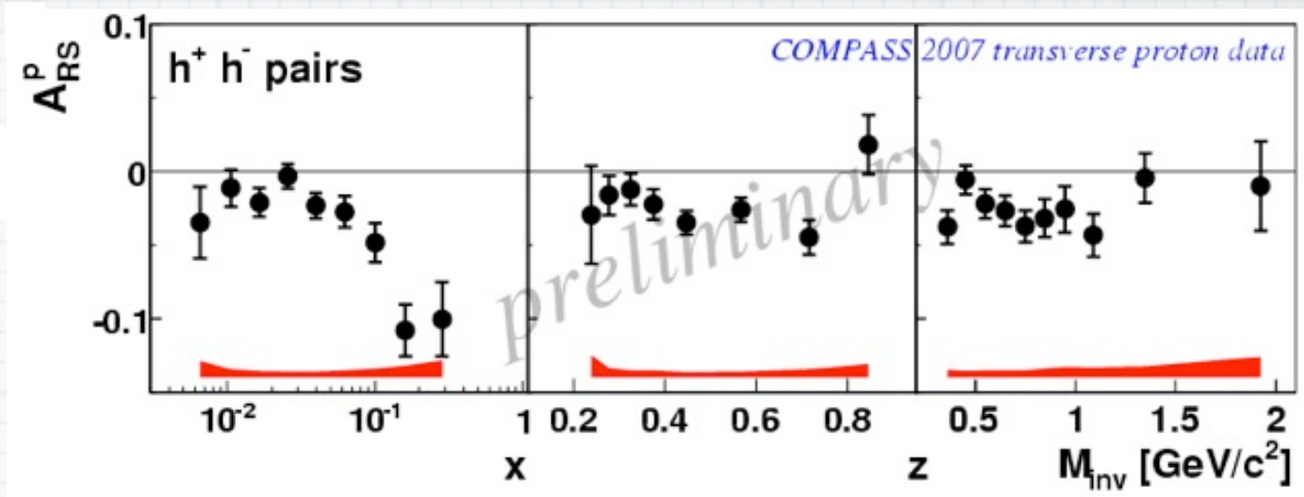
[A. Airapetian et al., JHEP 06 (2008) 017]



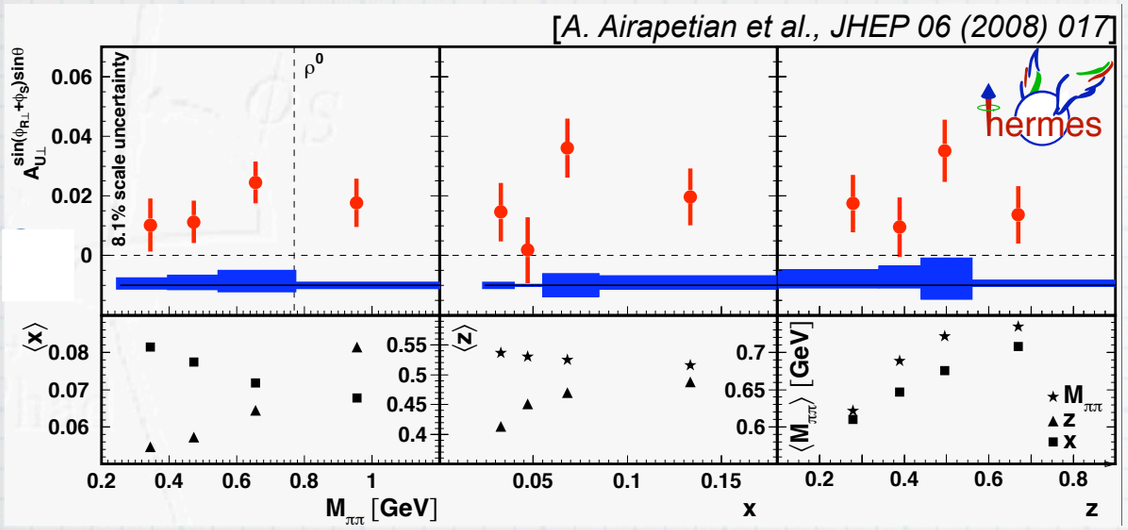


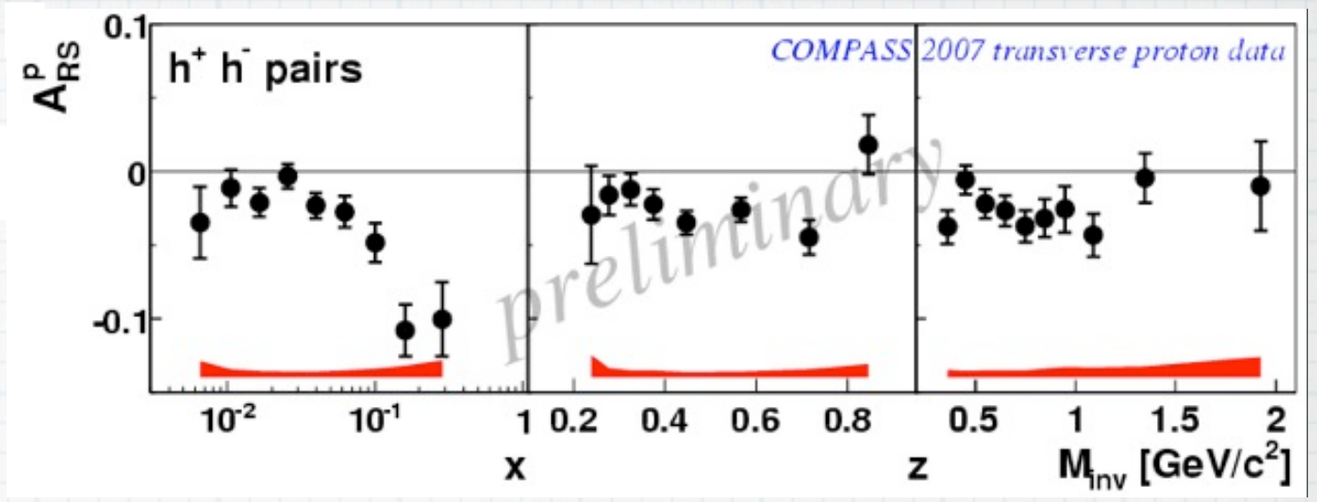
2-hadron production

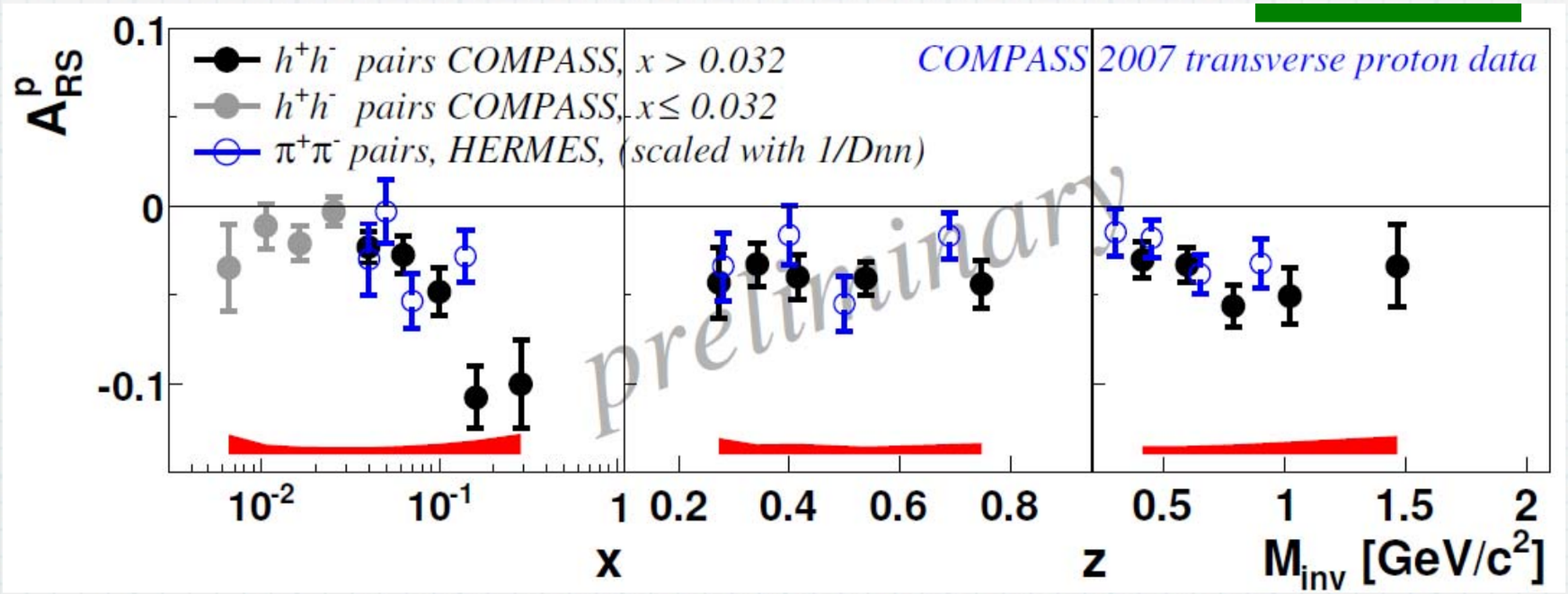




2-hadron production







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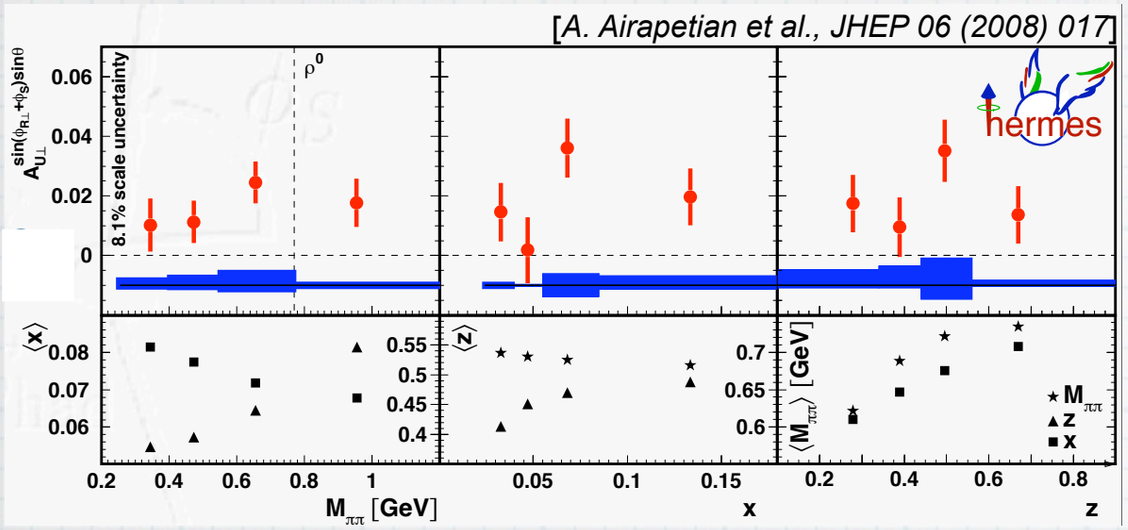
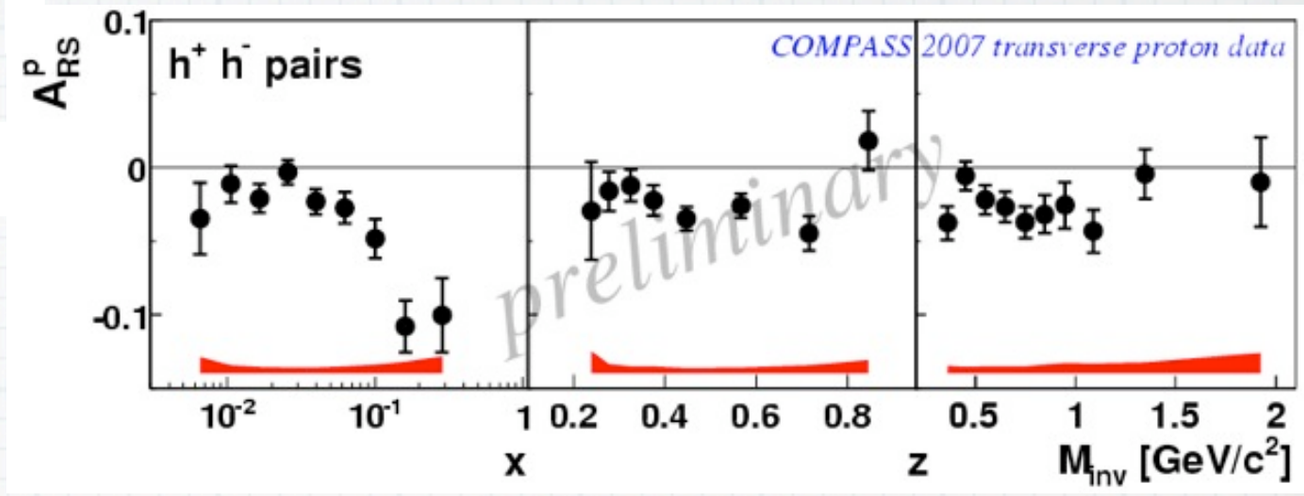
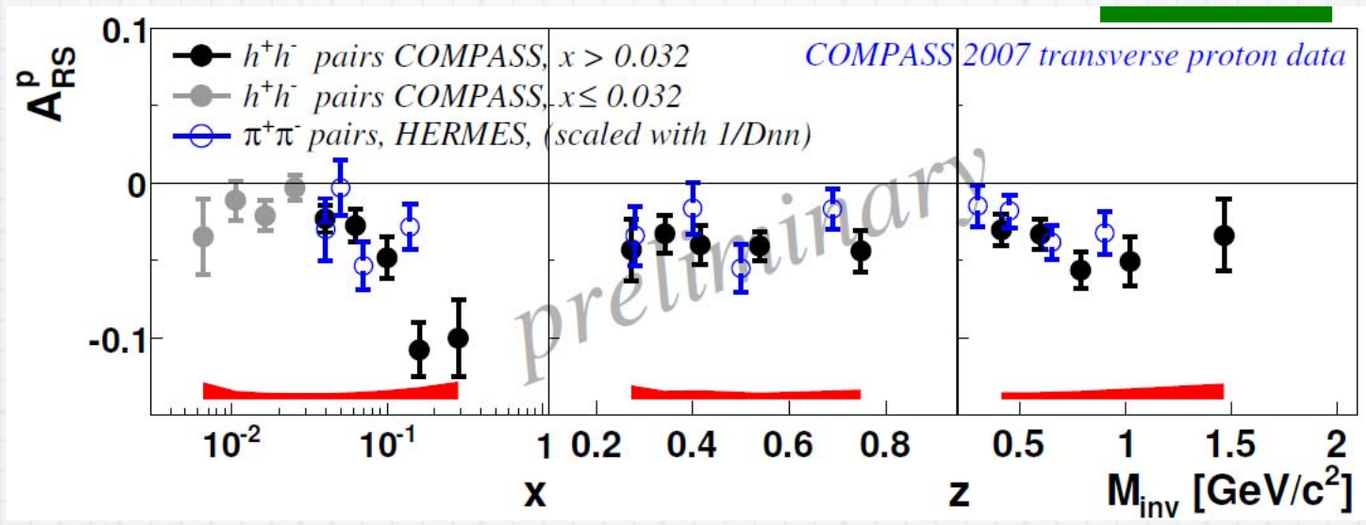
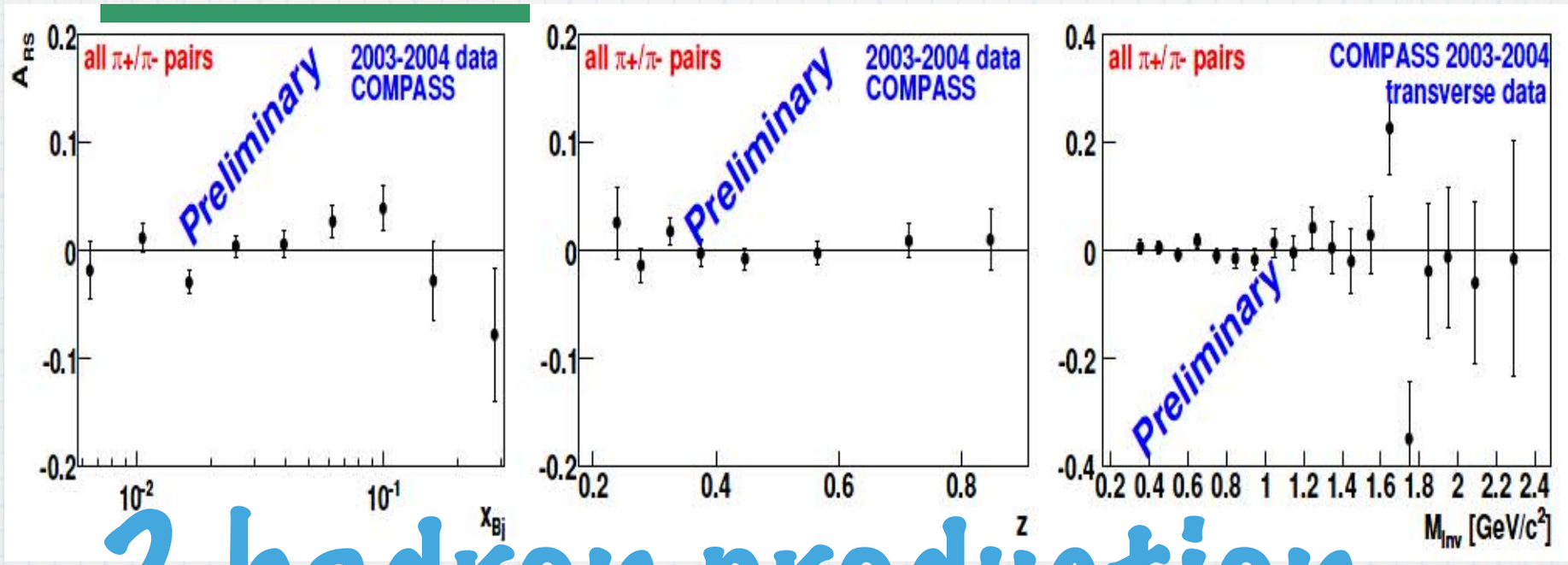
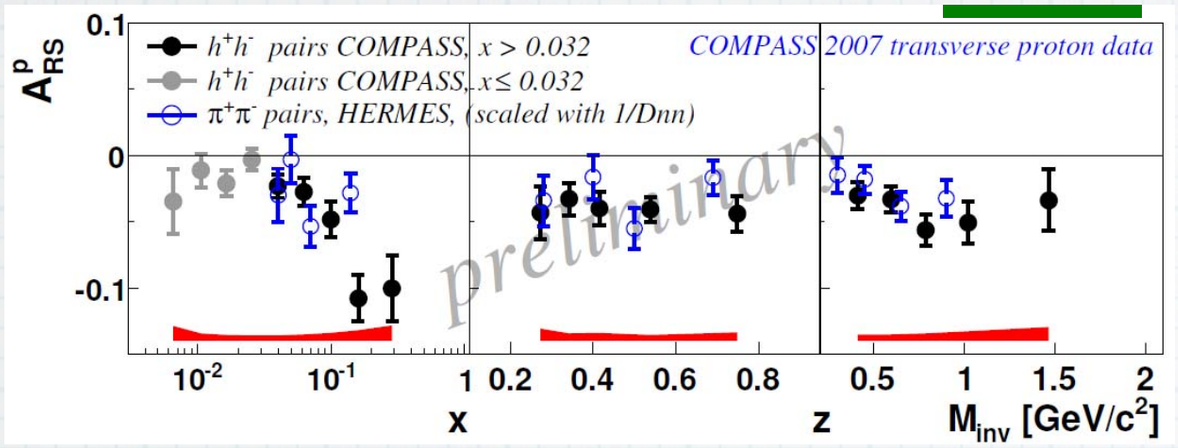


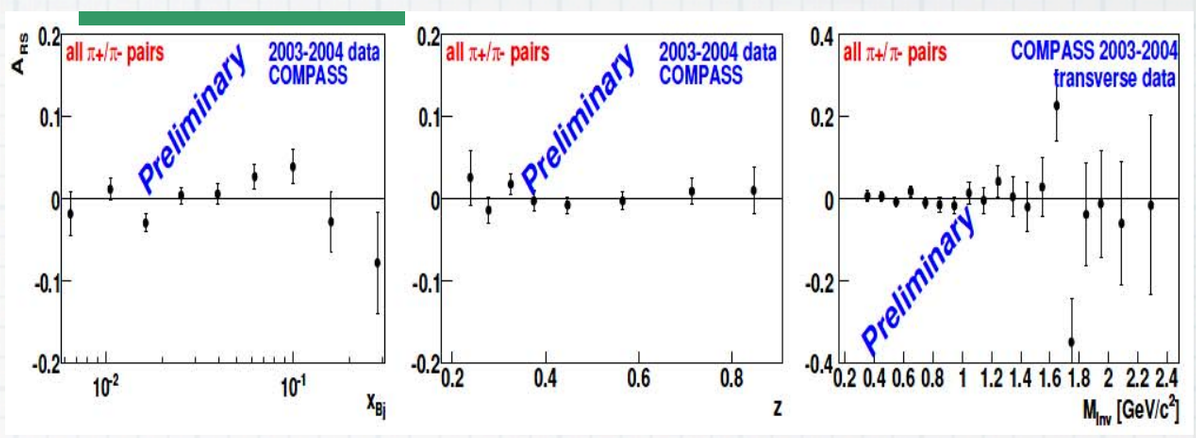






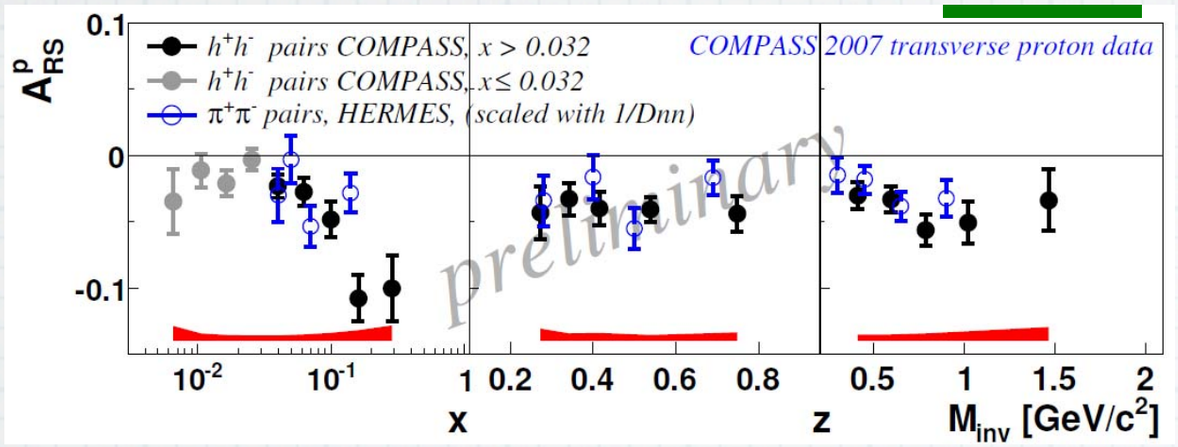
2-hadron production

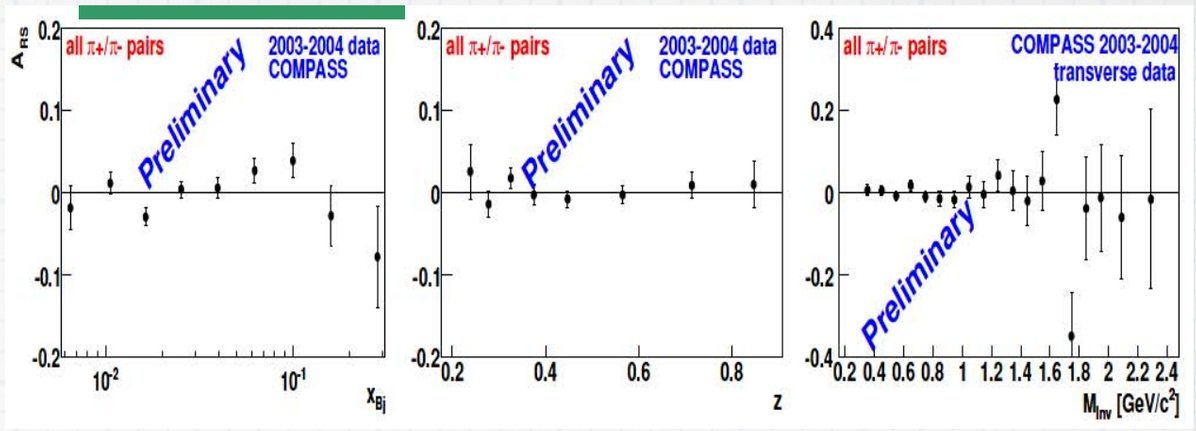




$$A_{UT} \propto h_1 \times H_1^{\sphericalangle}$$

2-hadron production





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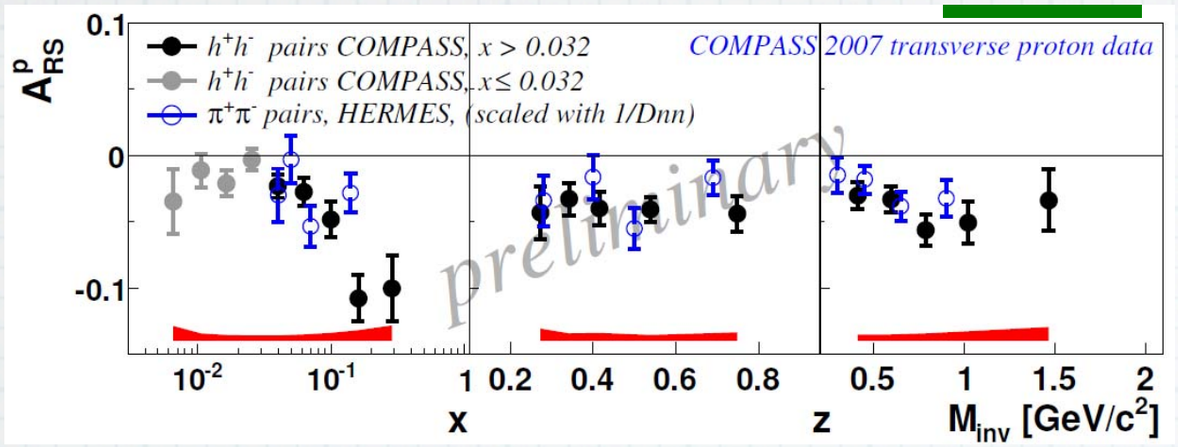
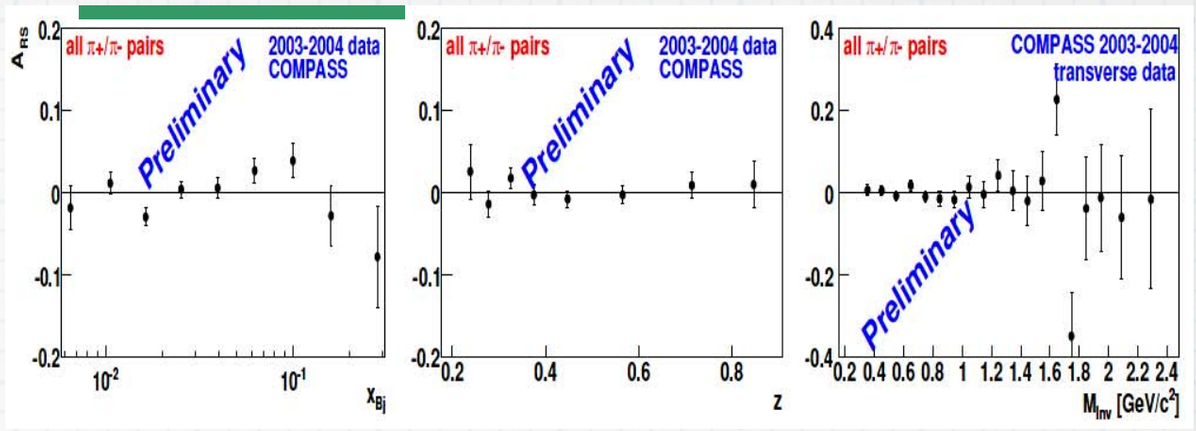
2-hadron production

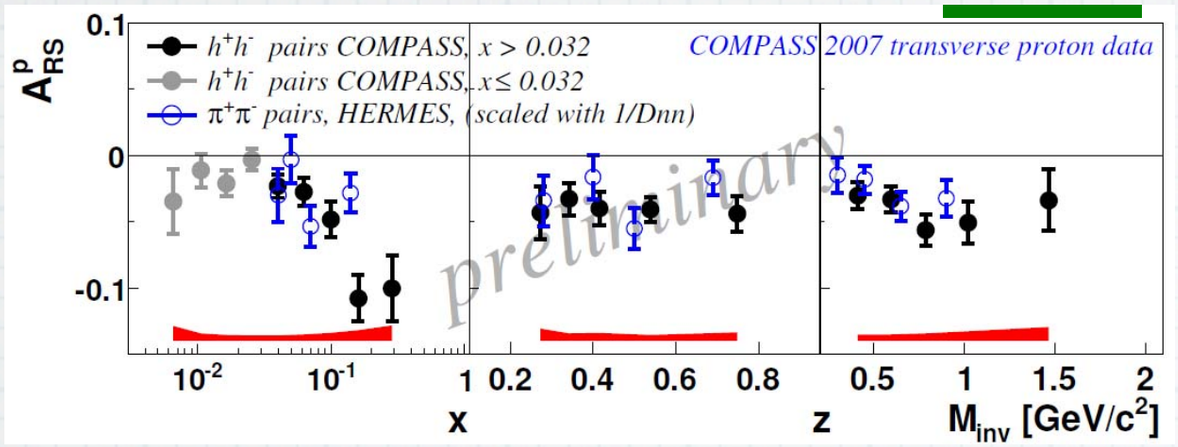


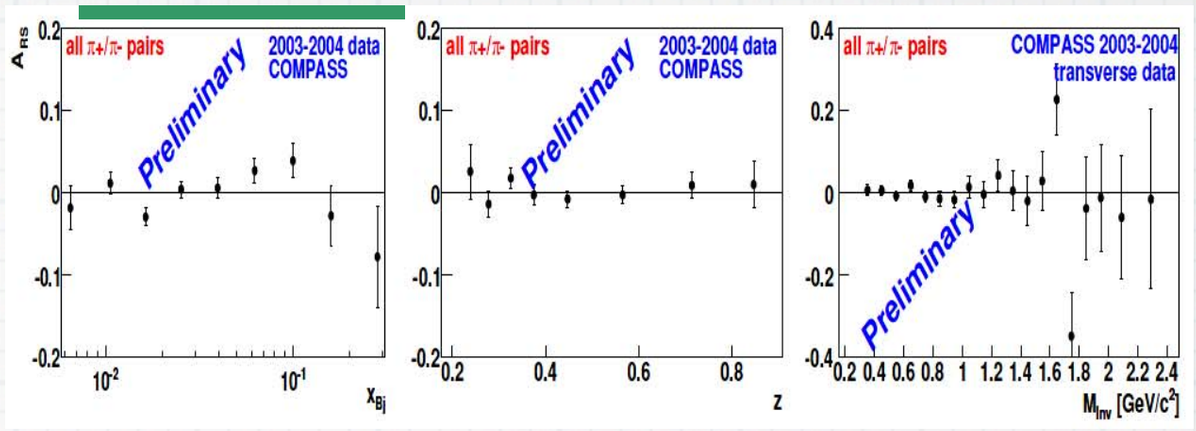


Direct product!
No assumption needed!

$$A_{UT} \propto h_1 \times H_1^{\sphericalangle}$$

2-hadron production





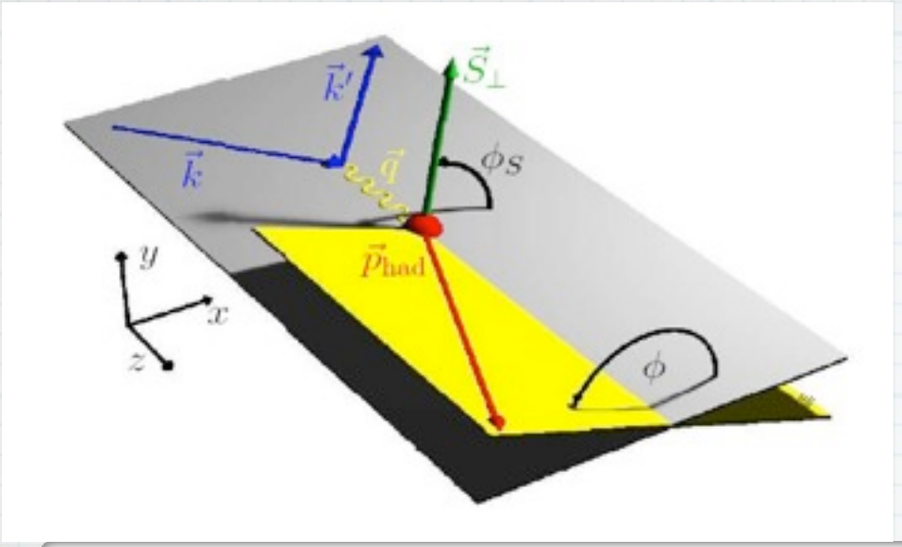
Direct product!
No assumption needed!

$$A_{UT} \propto h_1 \times H_1^{\sphericalangle}$$

hermes COMPASS BELLE

in progress...

2-hadron production



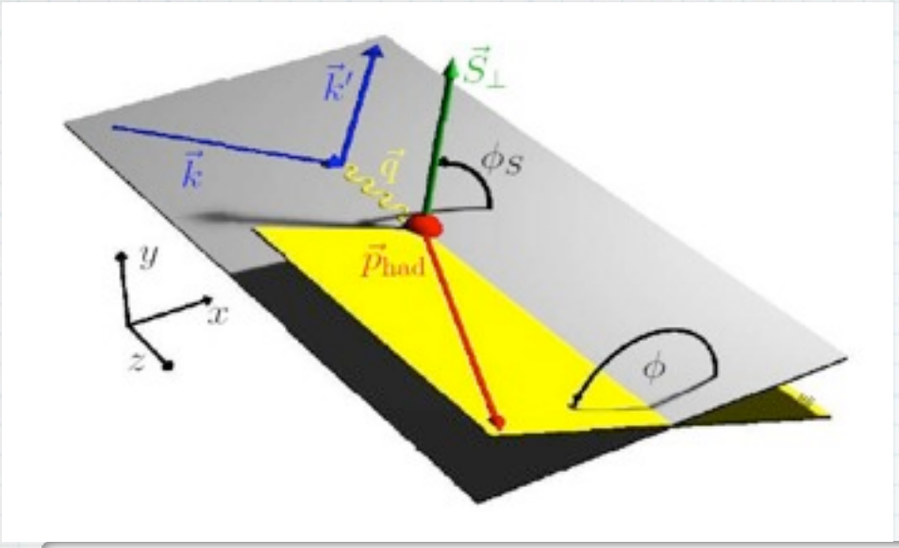
nucleon	quark: U	quark: L	quark: T
U	f_1 ○		
L		g_1 ⊙ − ⊙	
T			h_1 → − →

transverse longitudinal

nucleon spin

parton spin

parton transverse momentum



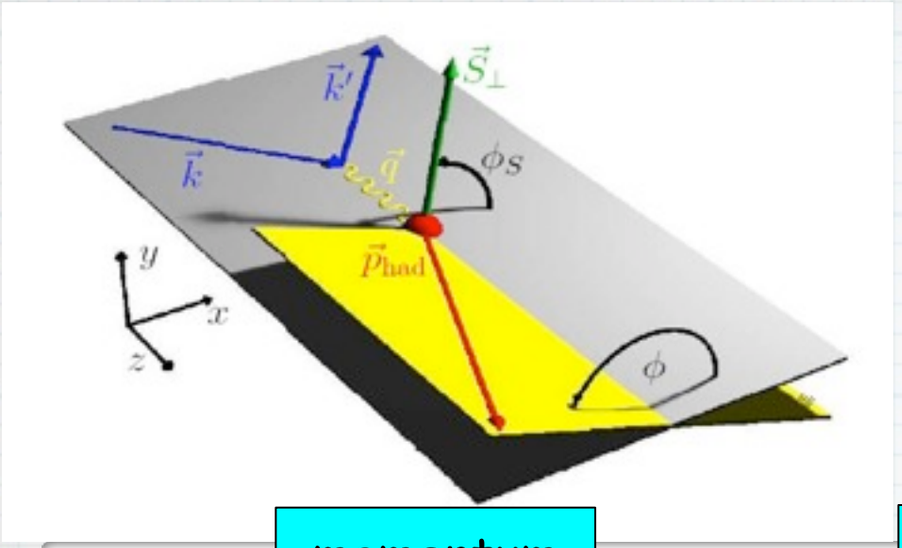
nucleon	quark: U	quark: L	quark: T
U	f_1 ○		$h_1^\perp$ ⟳ − ⟲
L		g_1 ⊙ − ⊗	$h_{1L}^\perp$ → − ←
T	$f_{1T}^\perp$ ↑ − ↓	$g_{1T}^\perp$ → − ←	h_1 → − ← $h_{1T}^\perp$ → − ←

transverse longitudinal

nucleon spin

parton spin

parton transverse momentum



momentum

helicity

nucleon	quark U	quark L	quark T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	$g_{1T}^\perp$	h_1, $h_{1T}^\perp$

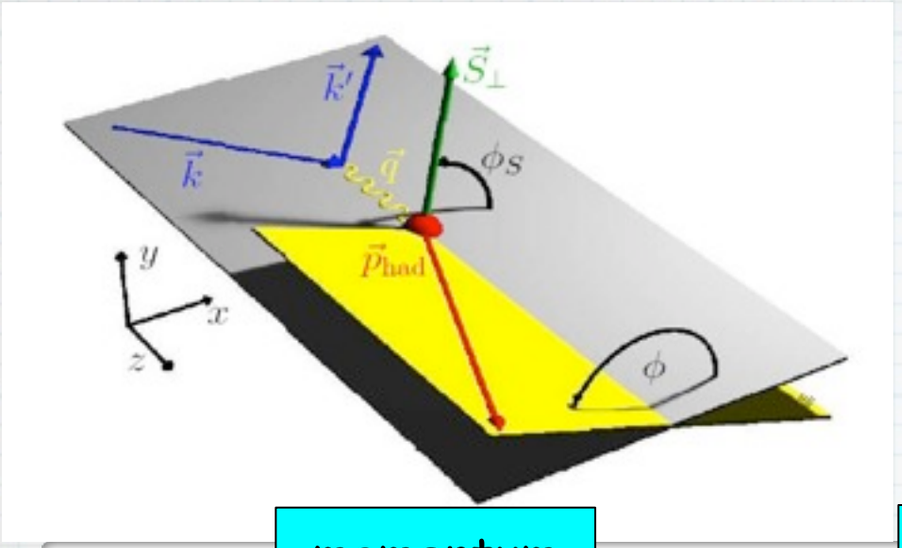
transversity

transverse longitudinal

nucleon spin

parton spin

parton transverse momentum



momentum

helicity

Boer-Mulders

nucleon	quark U	quark L	quark T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	$g_{1T}^\perp$	h_1, $h_{1T}^\perp$

Sivers

worm-gears

transversity

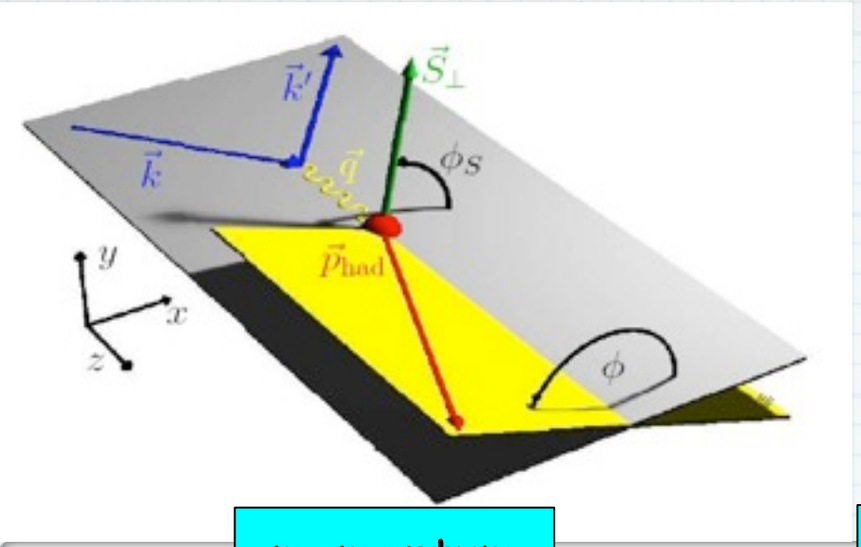
pretzelosity

transverse longitudinal

nucleon spin

parton spin

parton transverse momentum



momentum

helicity

Boer-Mulders

nucleon	quark U	quark L	quark T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	$g_{1T}^\perp$	h_1, $h_{1T}^\perp$

Sivers

worm-gears

transversity

pretzelosity

$$\frac{d\sigma^h}{dx\,dy\,d\phi_S\,dz\,d\phi\,d\mathbf{P}_{h\perp}^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right)$$

$$\Big\{ \Big[F_{UU,T} + \epsilon F_{UU,L} + \sqrt{2\epsilon(1+\epsilon)}\cos(\phi)F_{UU}^{\cos\phi} + \epsilon\cos(2\phi)F_{UU}^{\cos 2\phi}\Big]$$

$$+ \lambda_l\Big[\sqrt{2\epsilon(1-\epsilon)}\sin(\phi)F_{LU}^{\sin\phi}\Big]$$

$$+ S_L\Big[\sqrt{2\epsilon(1+\epsilon)}\sin(\phi)F_{UL}^{\sin\phi} + \epsilon\sin(2\phi)F_{UL}^{\sin 2\phi}\Big]$$

$$+ S_L\Big[\sqrt{1-\epsilon^2}F_{LL} + \sqrt{2\epsilon(1-\epsilon)}\cos(\phi)F_{LL}^{\cos\phi}\Big]$$

$$+ S_T\Big[\sin(\phi-\phi_S)\left(F_{UT,T}^{\sin(\phi-\phi_S)} + \epsilon F_{UT,L}^{\sin(\phi-\phi_S)}\right) + \epsilon\sin(\phi+\phi_S)F_{UT}^{\sin(\phi+\phi_S)} + \epsilon\sin(3\phi-\phi_S)F_{UT}^{\sin(3\phi-\phi_S)} + \sqrt{2\epsilon(1+\epsilon)}\sin(\phi_S)F_{UT}^{\sin\phi_S} + \sqrt{2\epsilon(1+\epsilon)}\sin(2\phi-\phi_S)F_{UT}^{\sin(2\phi-\phi_S)}\Big]$$

$$+ S_T\lambda_l\Big[\sqrt{1-\epsilon^2}\cos(\phi-\phi_S)F_{LT}^{\cos(\phi-\phi_S)} + \sqrt{2\epsilon(1-\epsilon)}\cos(\phi_S)F_{LT}^{\cos\phi_S} + \sqrt{2\epsilon(1-\epsilon)}\cos(2\phi-\phi_S)F_{LT}^{\cos(2\phi-\phi_S)}\Big]\Big\}$$

transverse longitudinal

nucleon spin

parton spin

parton transverse momentum

Azimuthal asymmetry generated by correlation between quark transverse momentum

Sivers & Boer-Mulders

FRANCESCA GIORDANO

2011 RHIC & AGS ANNUAL USERS' MEETING

Azimuthal asymmetry generated by correlation between quark transverse momentum

the parton transverse spin

Boer-Mulders

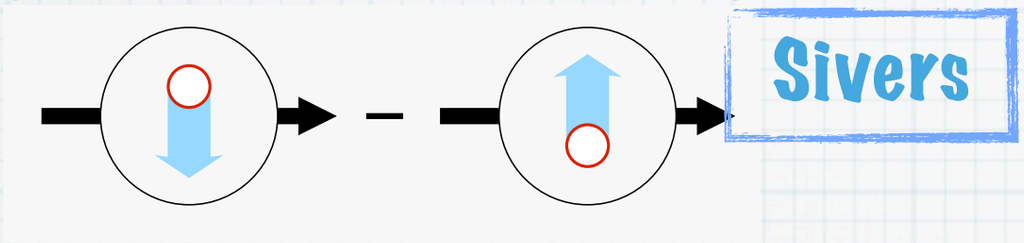
Sivers & Boer-Mulders

FRANCESCA GIORDANO

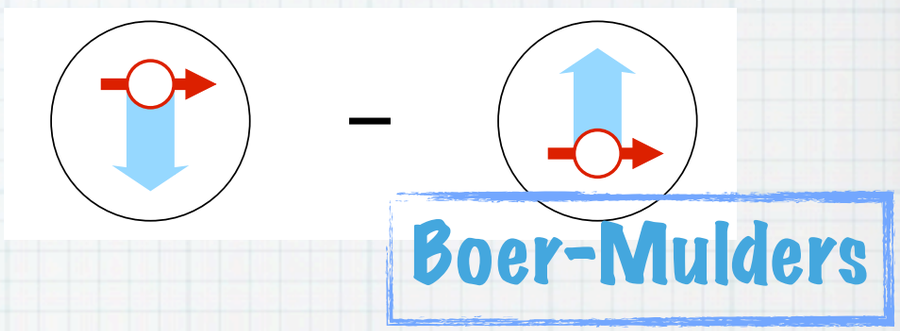
2011 RHIC & AGS ANNUAL USERS' MEETING

Azimuthal asymmetry generated by correlation between quark transverse momentum

the proton transverse spin



the parton transverse spin



Sivers & Boer-Mulders

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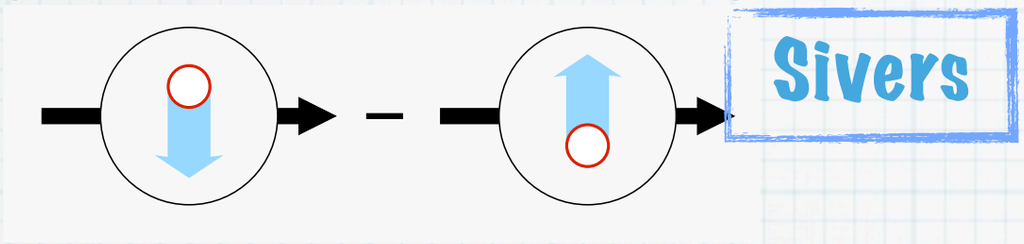
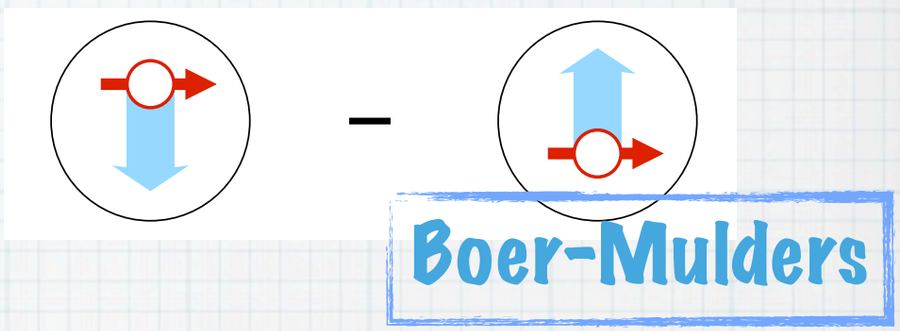
Azimuthal asymmetry generated by correlation between quark transverse momentum

the proton transverse spin



the parton transverse spin



Both are Naively T-odd

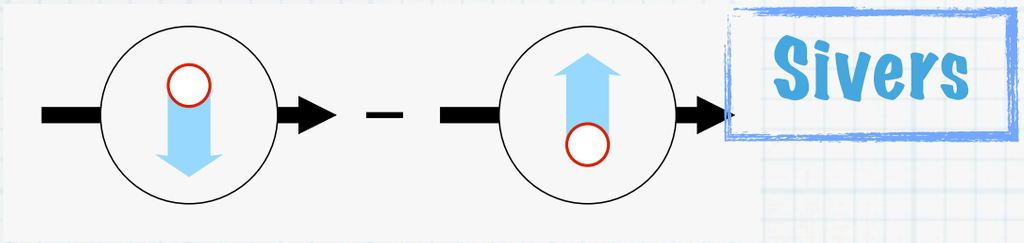
Sivers & Boer-Mulders

FRANCESCA GIORDANO

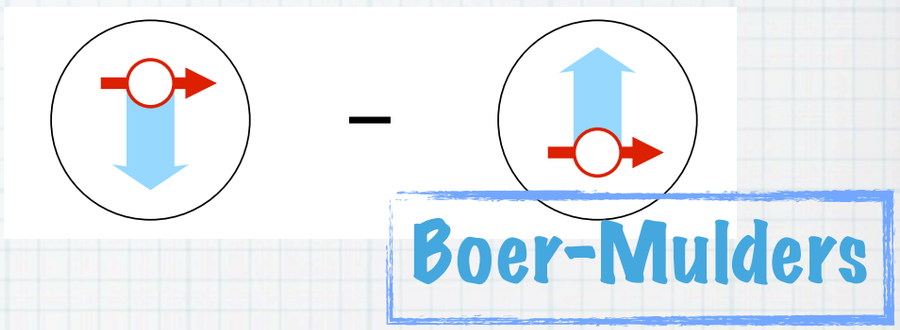
2011 RHIC & AGS ANNUAL USERS' MEETING

Azimuthal asymmetry generated by correlation between quark transverse momentum

the proton transverse spin

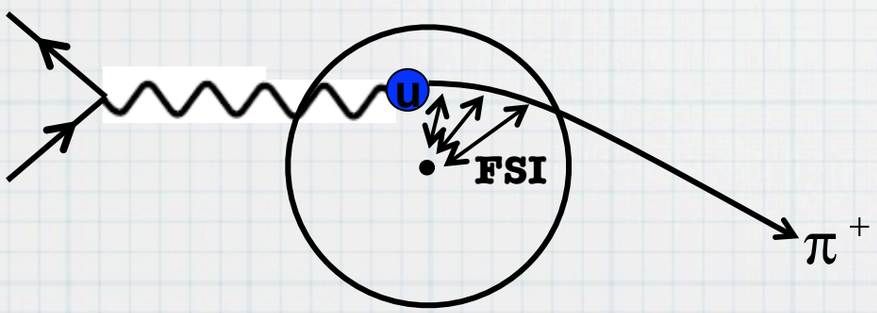


the parton transverse spin



Both are Naively T-odd

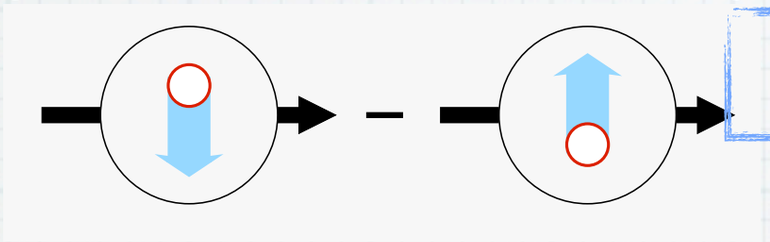
Final State Interaction



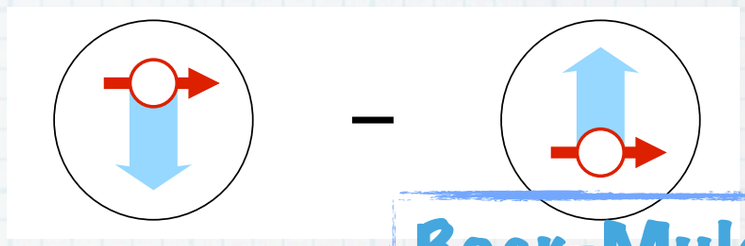
Sivers & Boer-Mulders

Azimuthal asymmetry generated by correlation between quark transverse momentum

the proton transverse spin

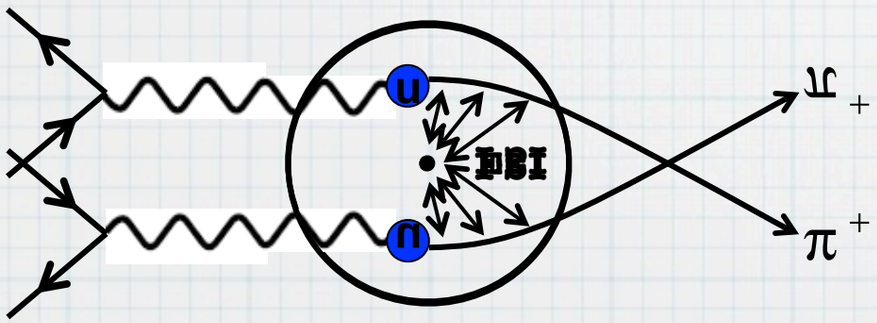


the parton transverse spin



Both are Naively T-odd

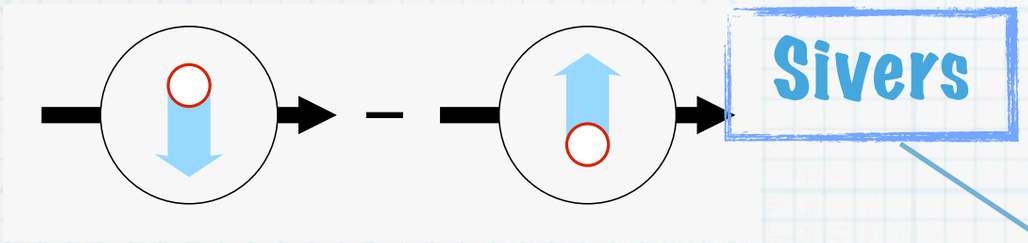
Final State Interaction



Sivers & Boer-Mulders

Azimuthal asymmetry generated by correlation between quark transverse momentum

the proton transverse spin



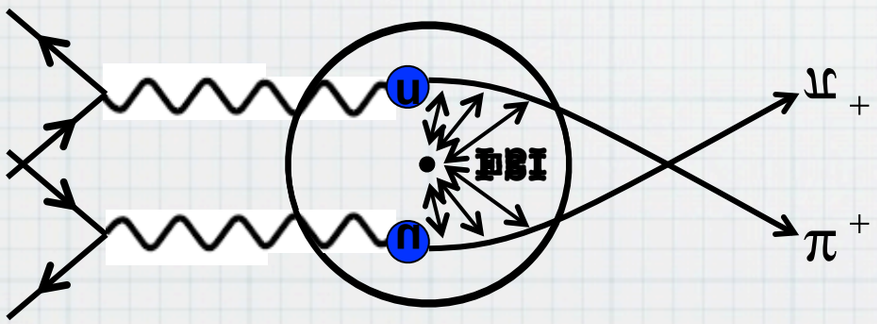
Sivers

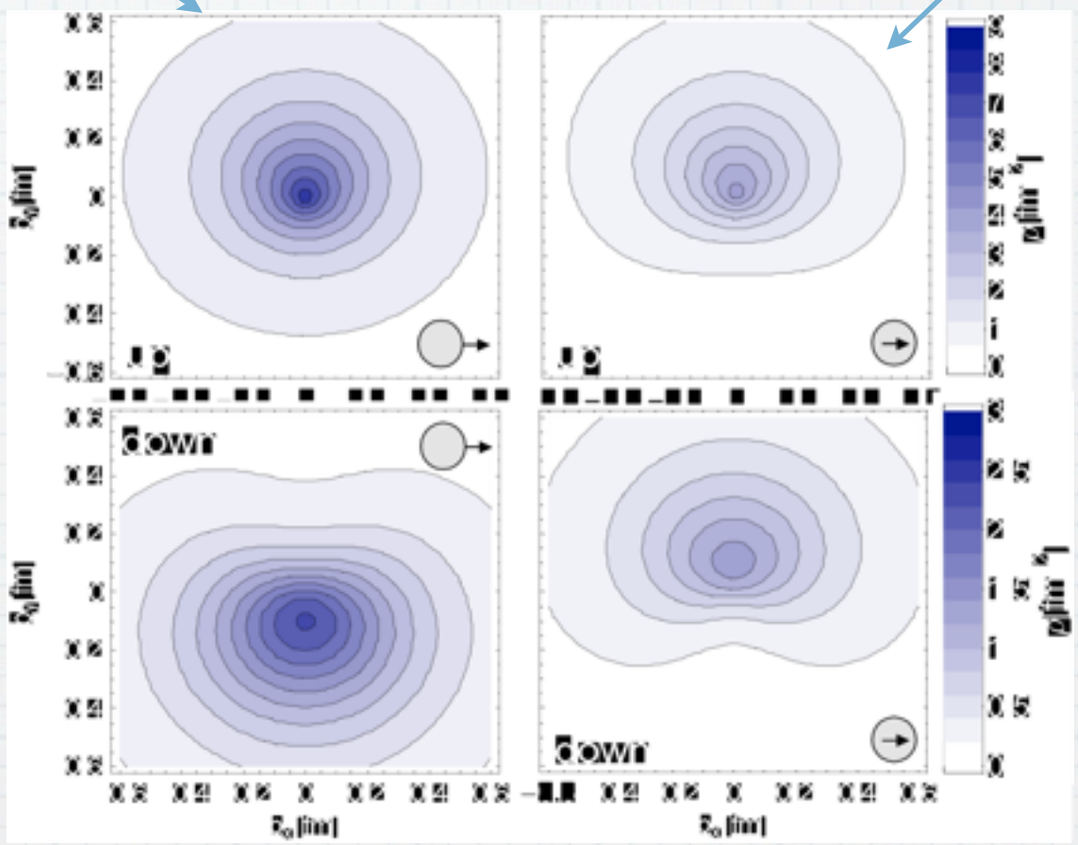
the parton transverse spin

Boer-Mulders

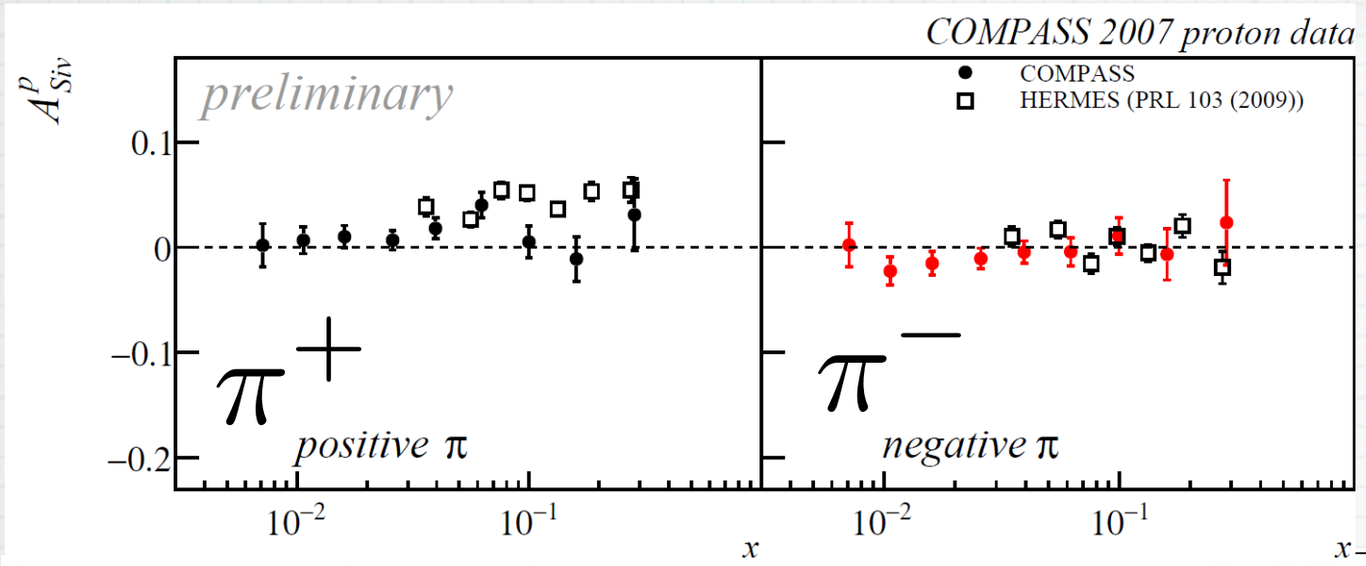
Both are Naively T-odd

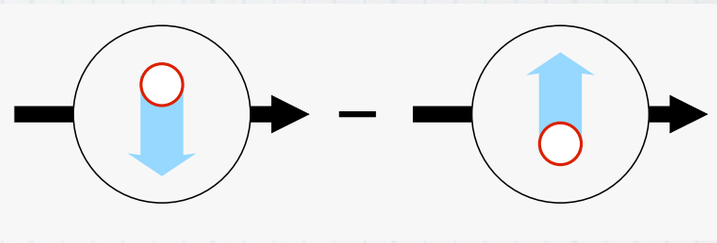
Final State Interaction

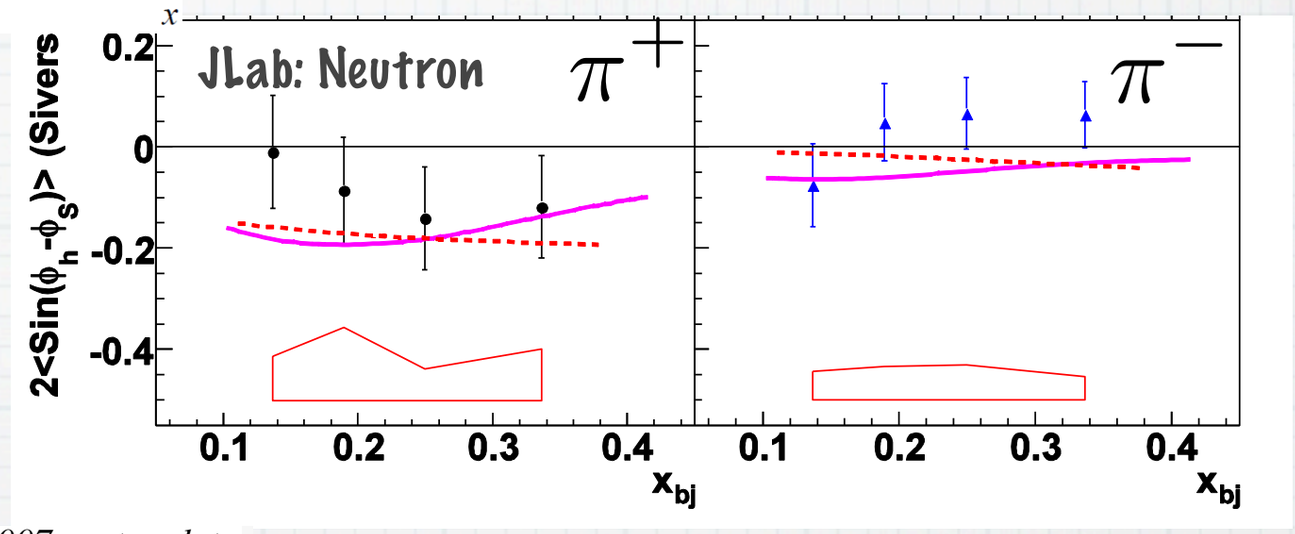


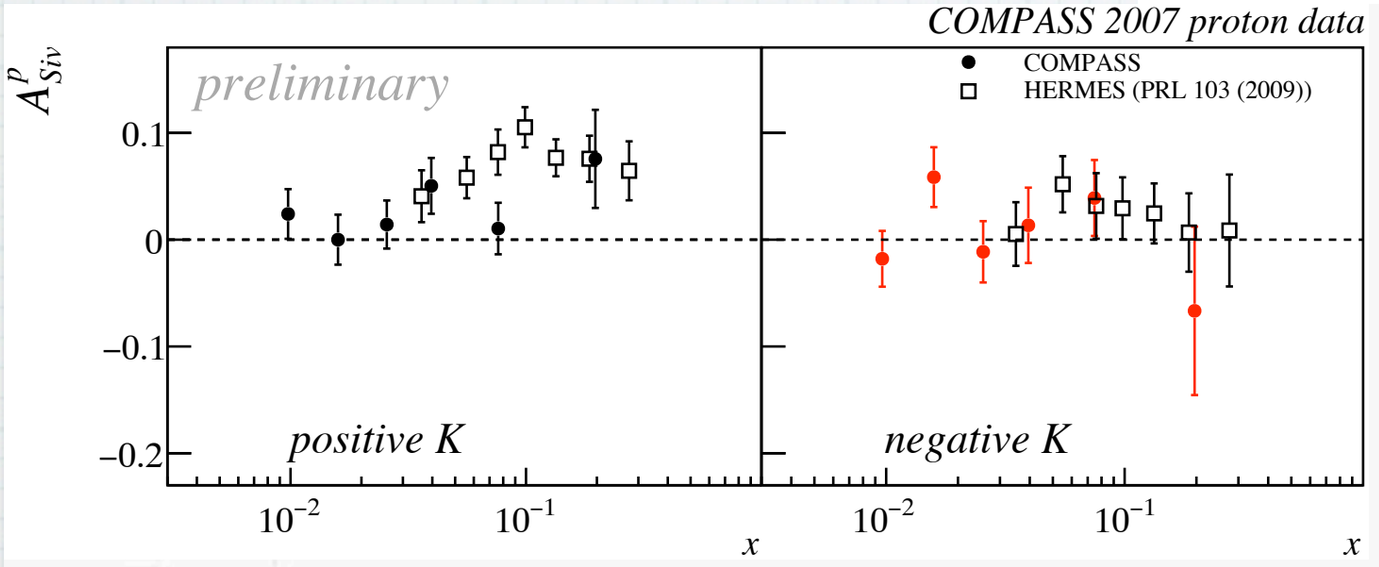


Sivers & Boer-Mulders

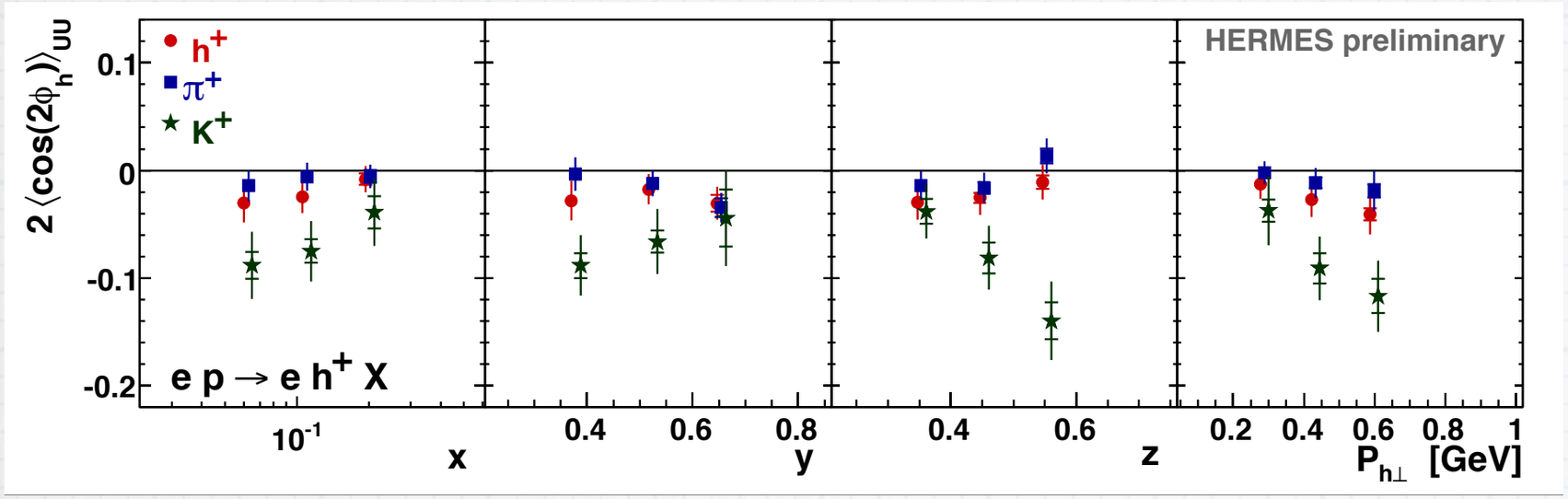


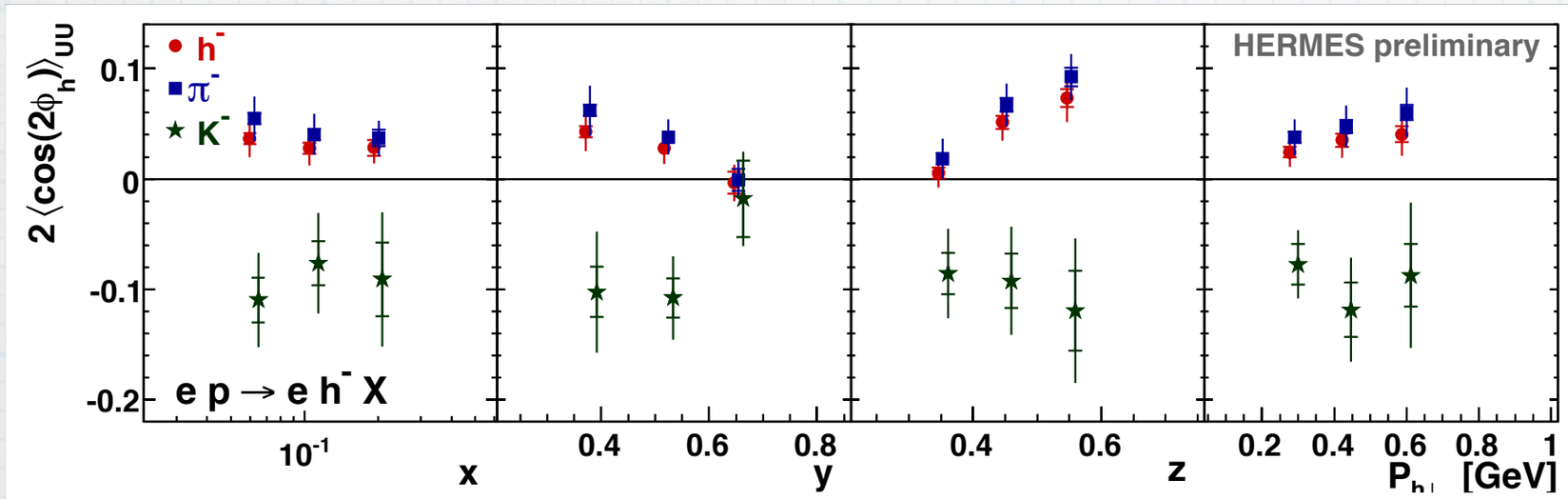


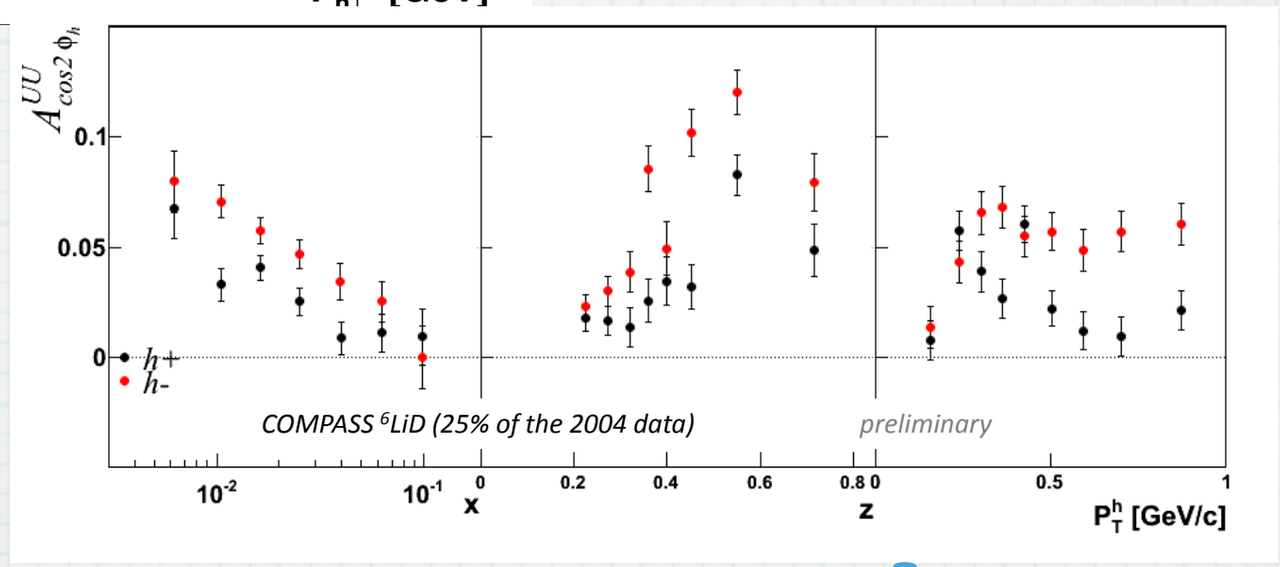




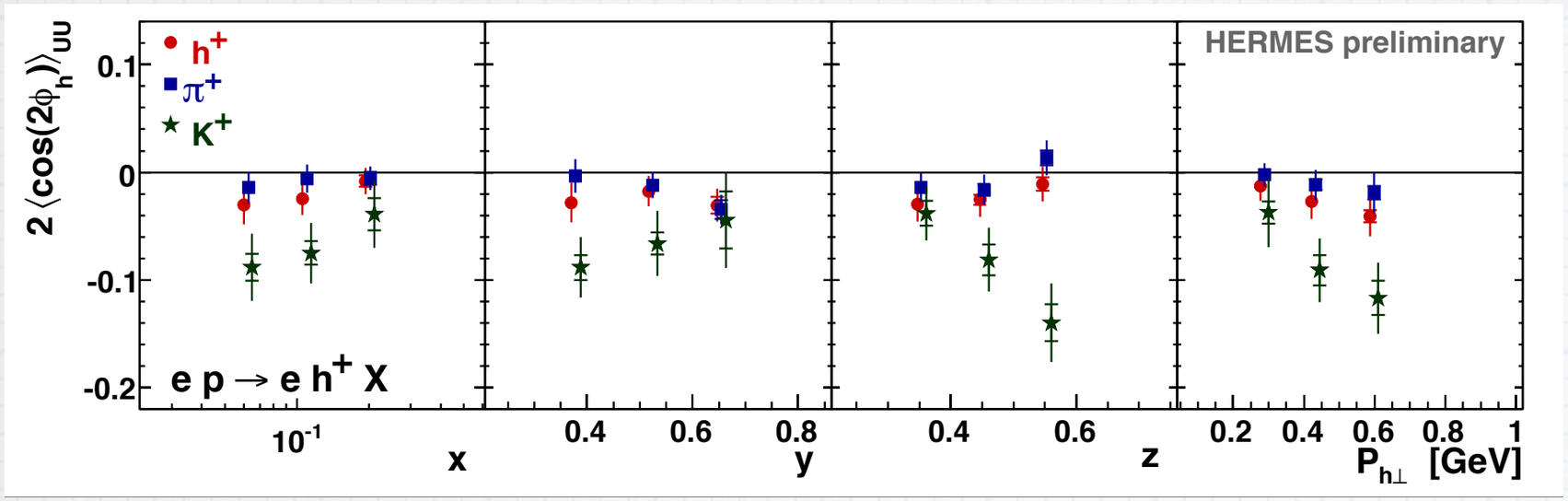
Sivers asymmetries

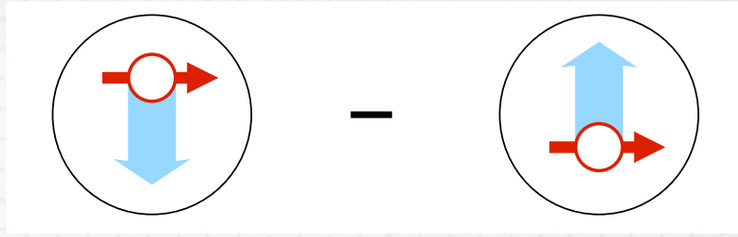


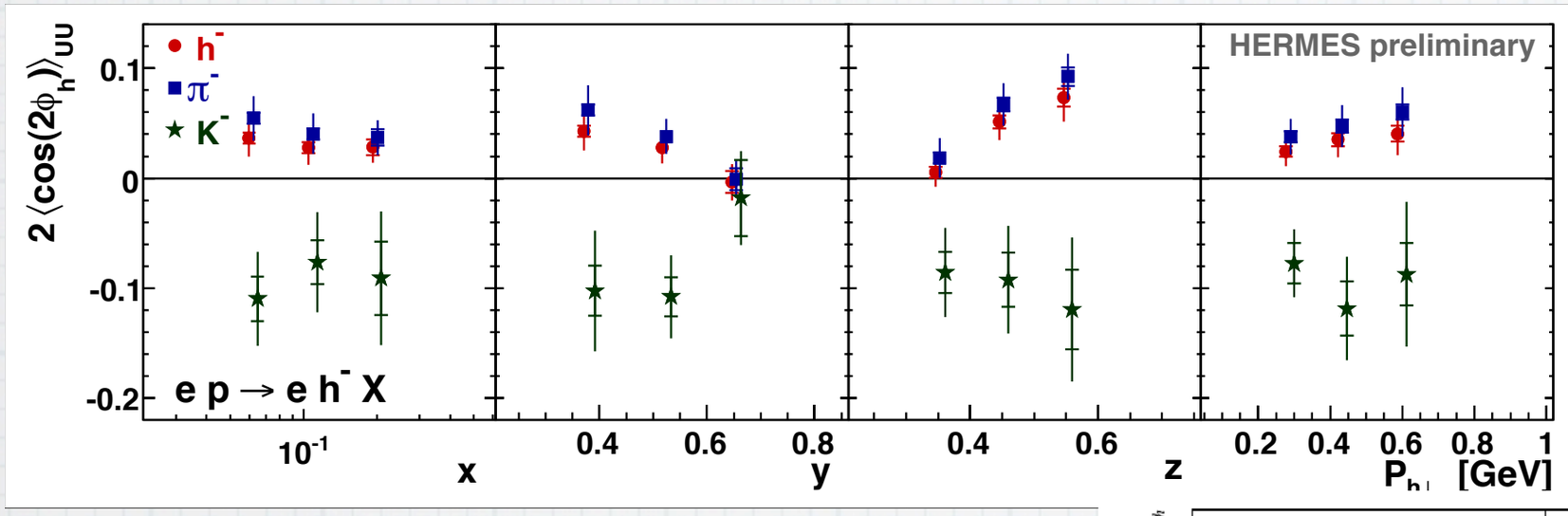


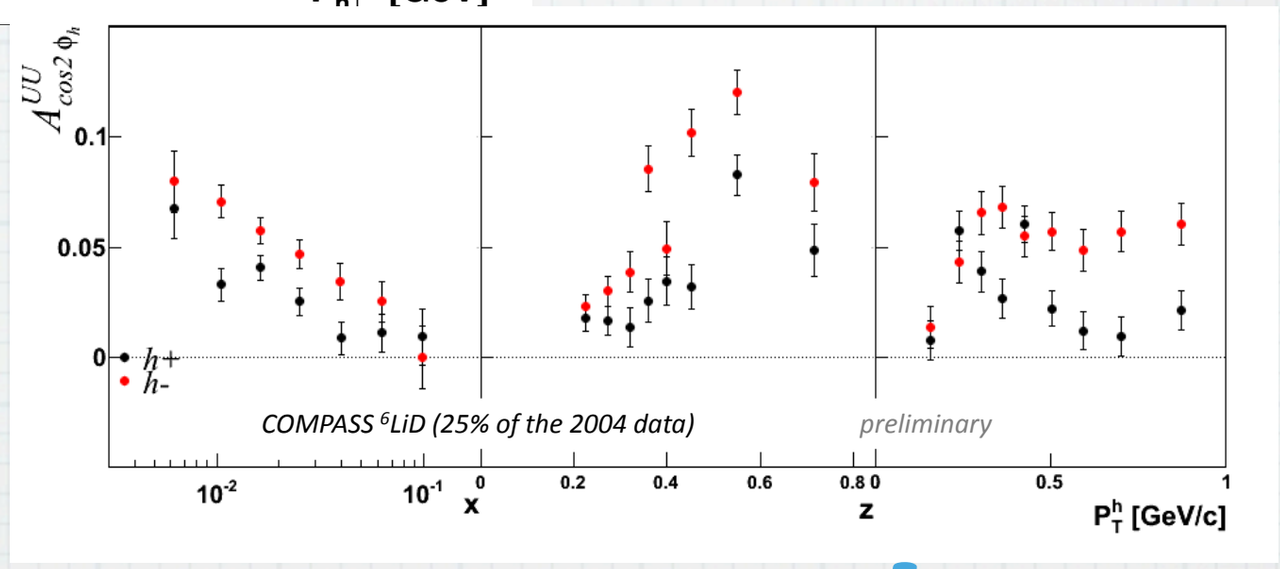


Boer-Mulders asymmetries

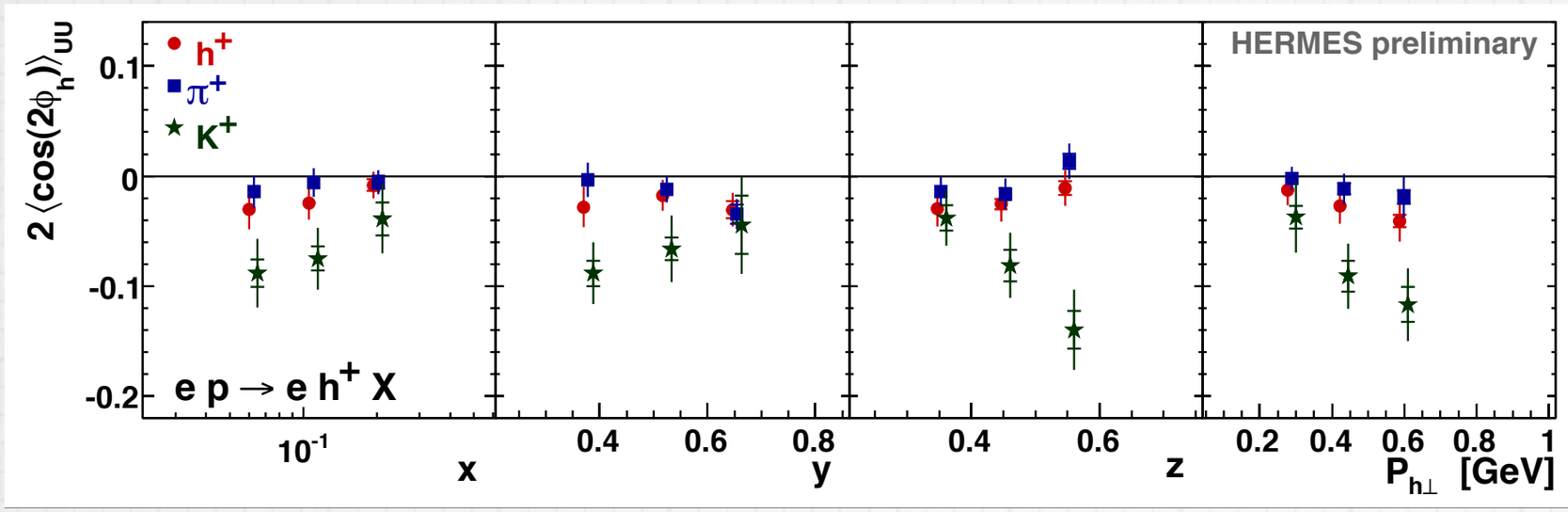


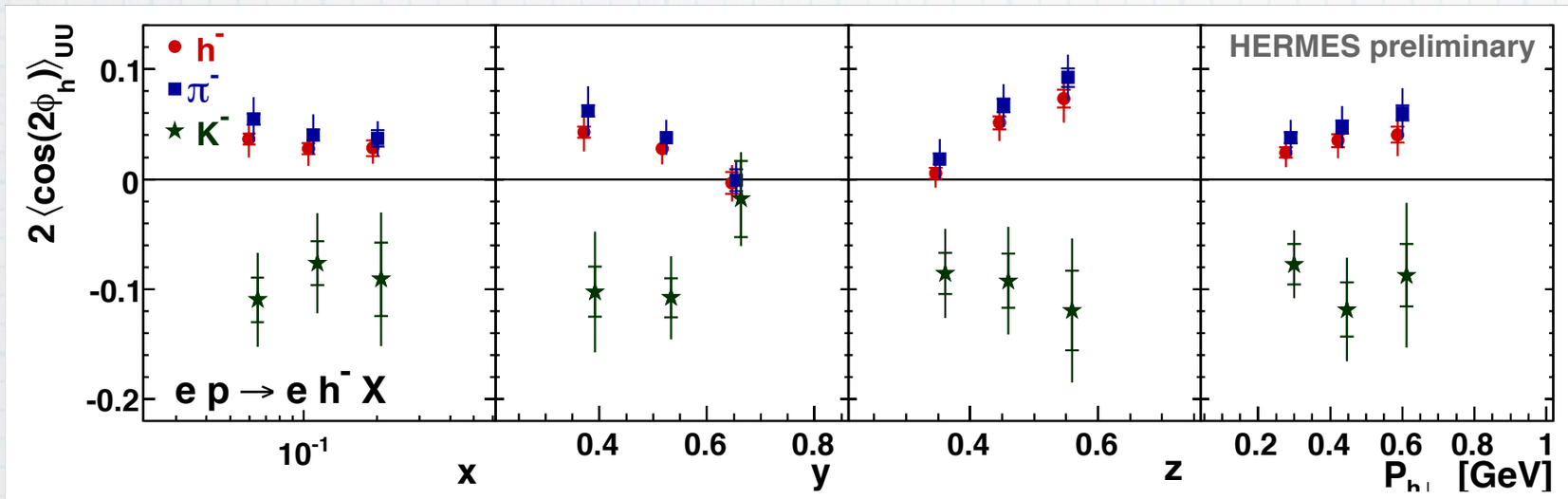




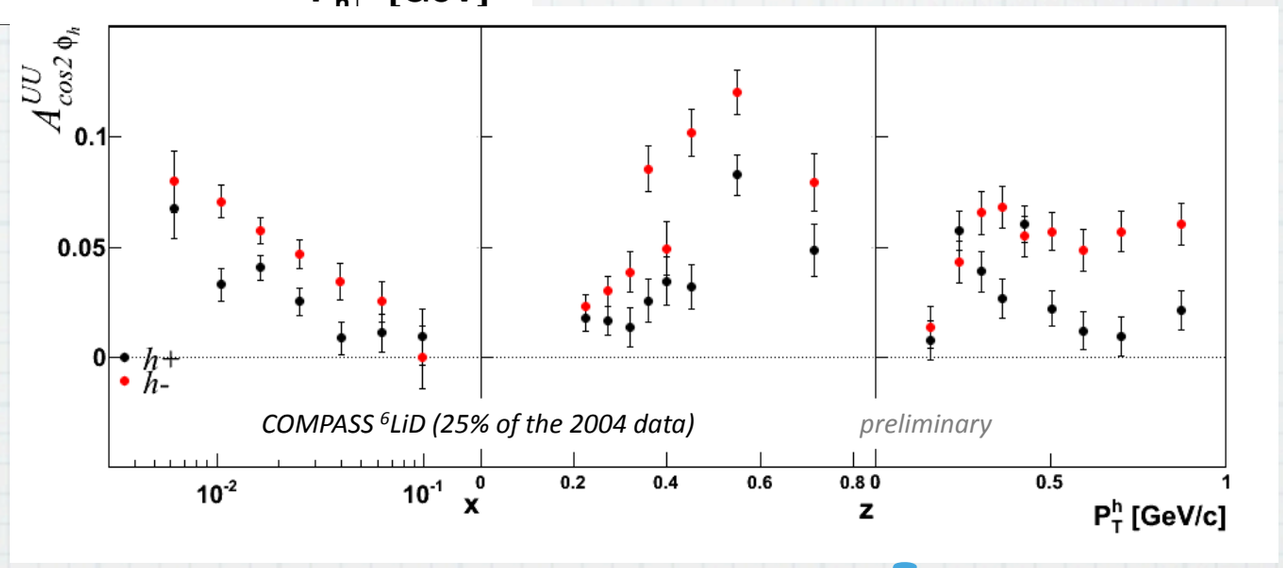


Boer-Mulders asymmetries

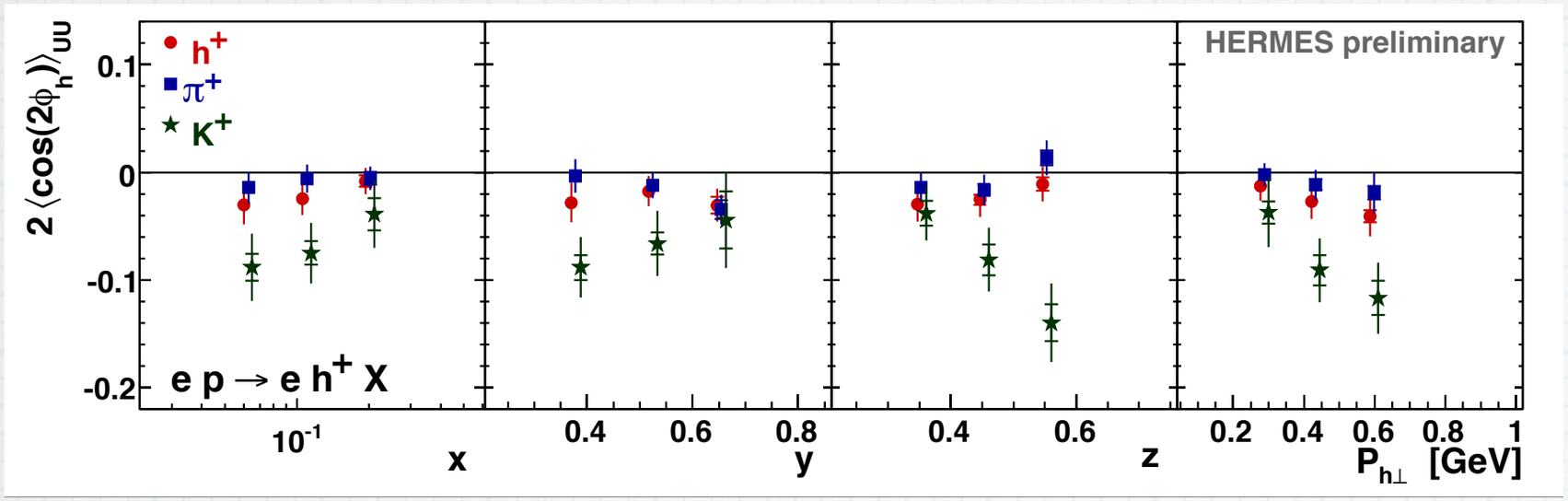


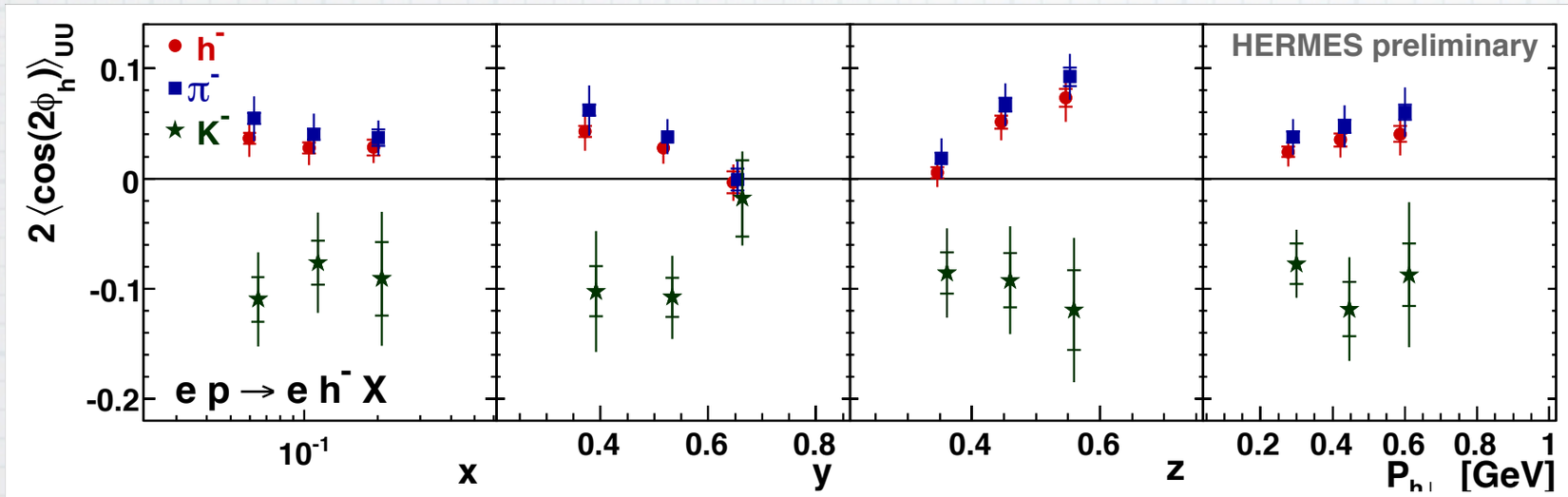


unpolarized target & beam:



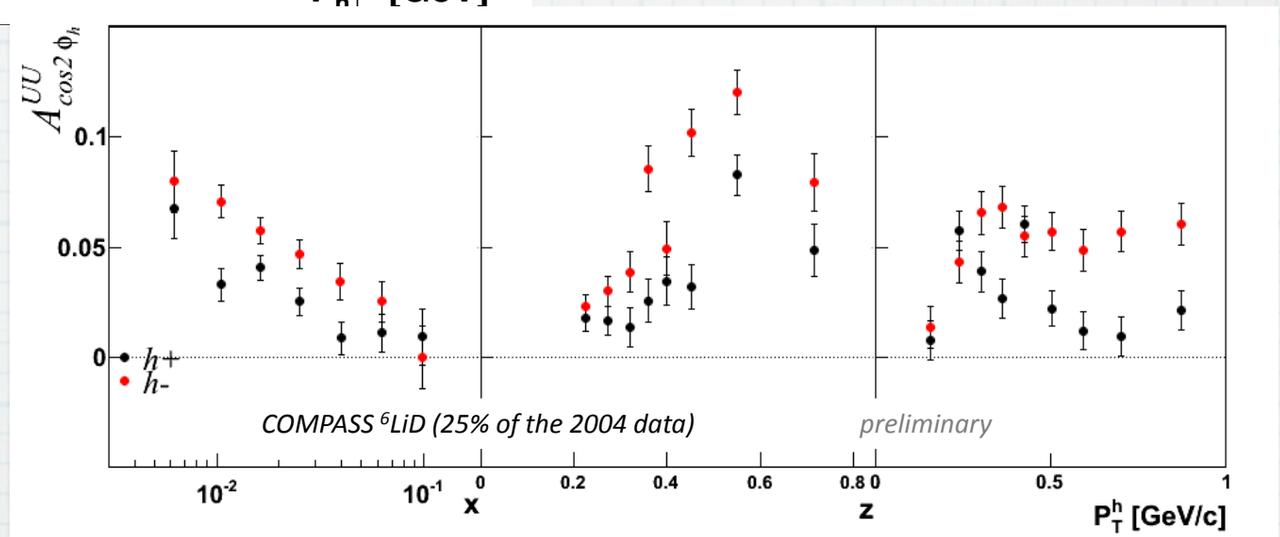
Boer-Mulders asymmetries



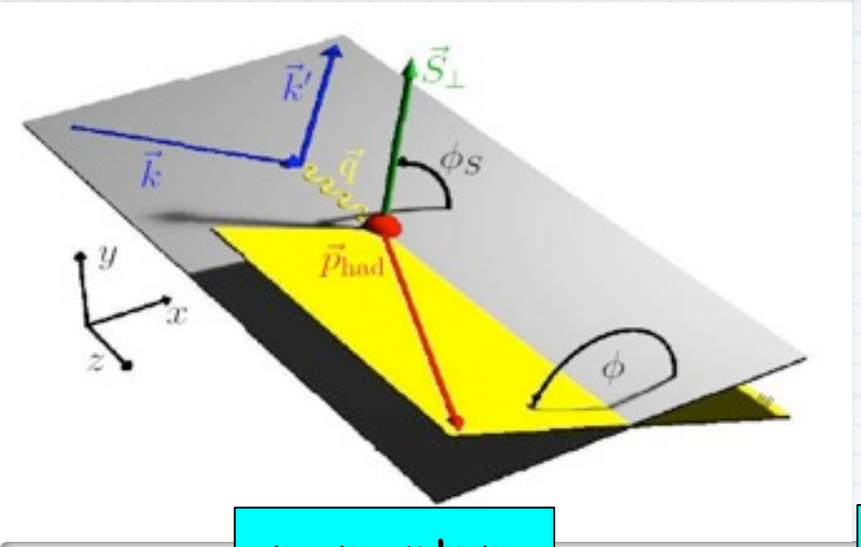


unpolarized target & beam:

spin effects also in unpolarized reactions!



Boer-Mulders asymmetries



momentum

helicity

Boer-Mulders

nucleon	quark U	quark L	quark T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	$g_{1T}^\perp$	h_1, $h_{1T}^\perp$

Sivers

worm-gears

transversity

pretzelosity

$$\frac{d\sigma^h}{dx\,dy\,d\phi_S\,dz\,d\phi\,d\mathbf{P}_{h\perp}^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right)$$

$$\Big\{ \Big[F_{UU,T} + \epsilon F_{UU,L} + \sqrt{2\epsilon(1+\epsilon)}\cos(\phi)F_{UU}^{\cos\phi} + \epsilon\cos(2\phi)F_{UU}^{\cos 2\phi}\Big]$$

$$+ \lambda_l\Big[\sqrt{2\epsilon(1-\epsilon)}\sin(\phi)F_{LU}^{\sin\phi}\Big]$$

$$+ S_L\Big[\sqrt{2\epsilon(1+\epsilon)}\sin(\phi)F_{UL}^{\sin\phi} + \epsilon\sin(2\phi)F_{UL}^{\sin 2\phi}\Big]$$

$$+ S_L\Big[\sqrt{1-\epsilon^2}F_{LL} + \sqrt{2\epsilon(1-\epsilon)}\cos(\phi)F_{LL}^{\cos\phi}\Big]$$

$$+ S_T\Big[\sin(\phi-\phi_S)\left(F_{UT,T}^{\sin(\phi-\phi_S)} + \epsilon F_{UT,L}^{\sin(\phi-\phi_S)}\right) + \epsilon\sin(\phi+\phi_S)F_{UT}^{\sin(\phi+\phi_S)} + \epsilon\sin(3\phi-\phi_S)F_{UT}^{\sin(3\phi-\phi_S)} + \sqrt{2\epsilon(1+\epsilon)}\sin(\phi_S)F_{UT}^{\sin\phi_S} + \sqrt{2\epsilon(1+\epsilon)}\sin(2\phi-\phi_S)F_{UT}^{\sin(2\phi-\phi_S)}\Big]$$

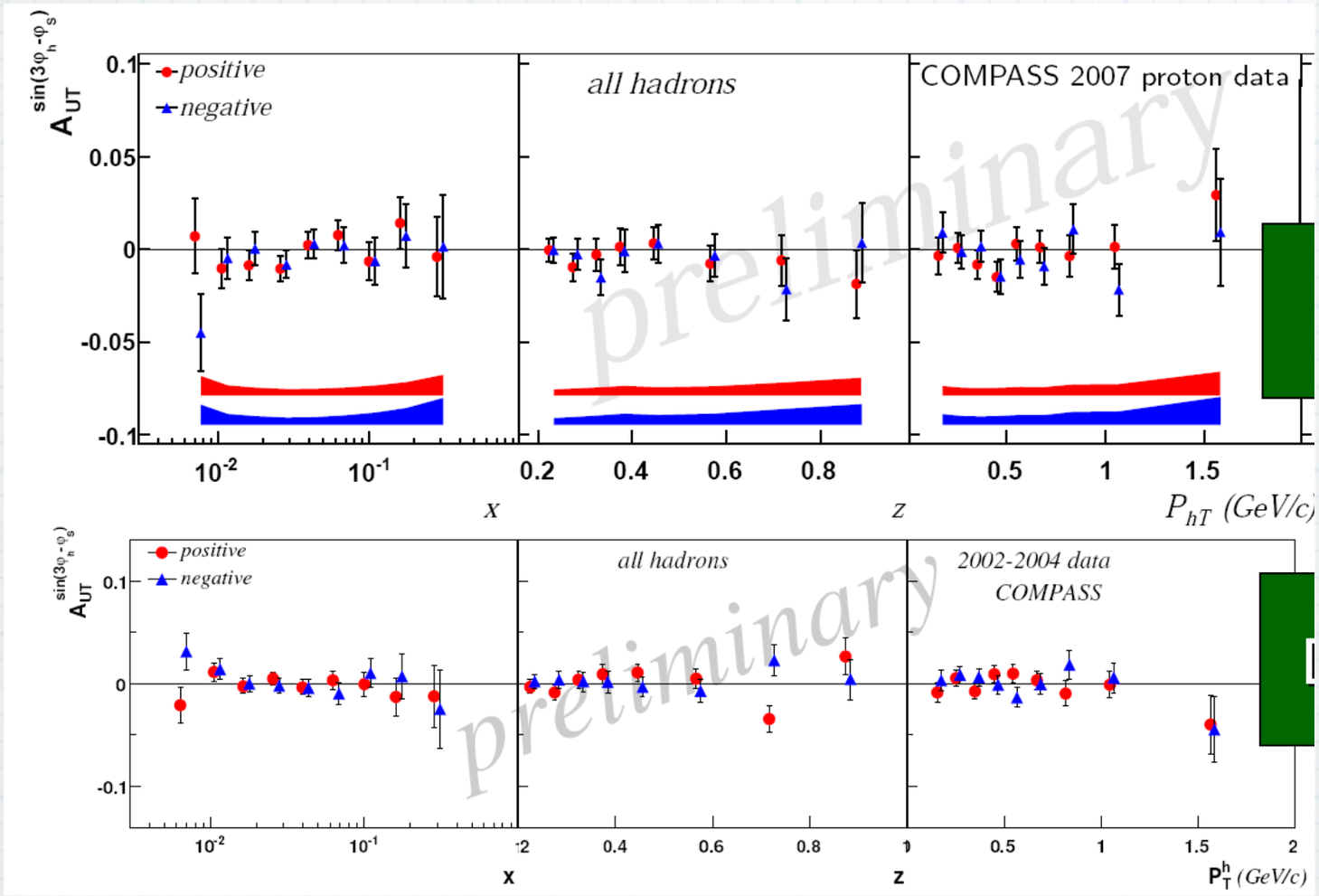
$$+ S_T\lambda_l\Big[\sqrt{1-\epsilon^2}\cos(\phi-\phi_S)F_{LT}^{\cos(\phi-\phi_S)} + \sqrt{2\epsilon(1-\epsilon)}\cos(\phi_S)F_{LT}^{\cos\phi_S} + \sqrt{2\epsilon(1-\epsilon)}\cos(2\phi-\phi_S)F_{LT}^{\cos(2\phi-\phi_S)}\Big]\Big\}$$

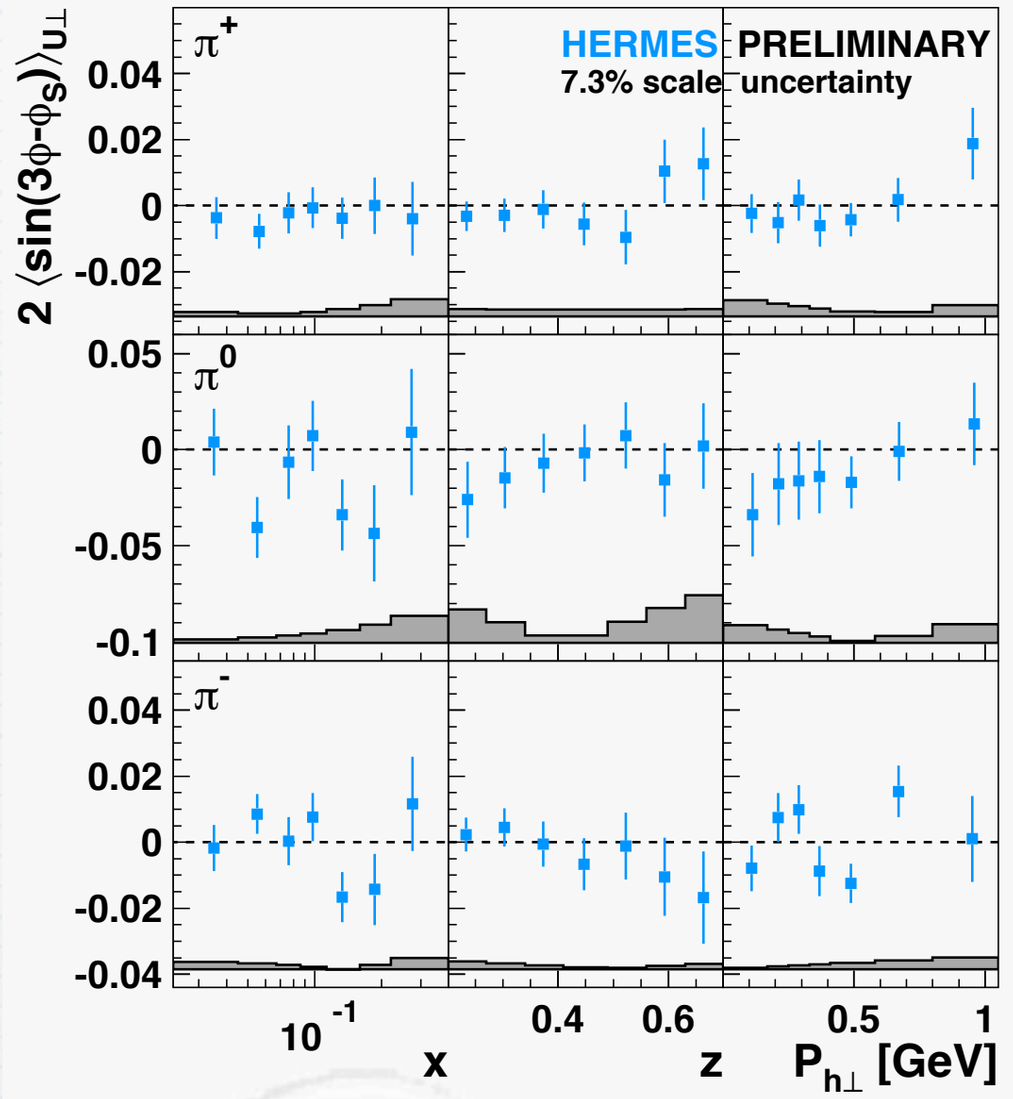
transverse longitudinal

nucleon spin

parton spin

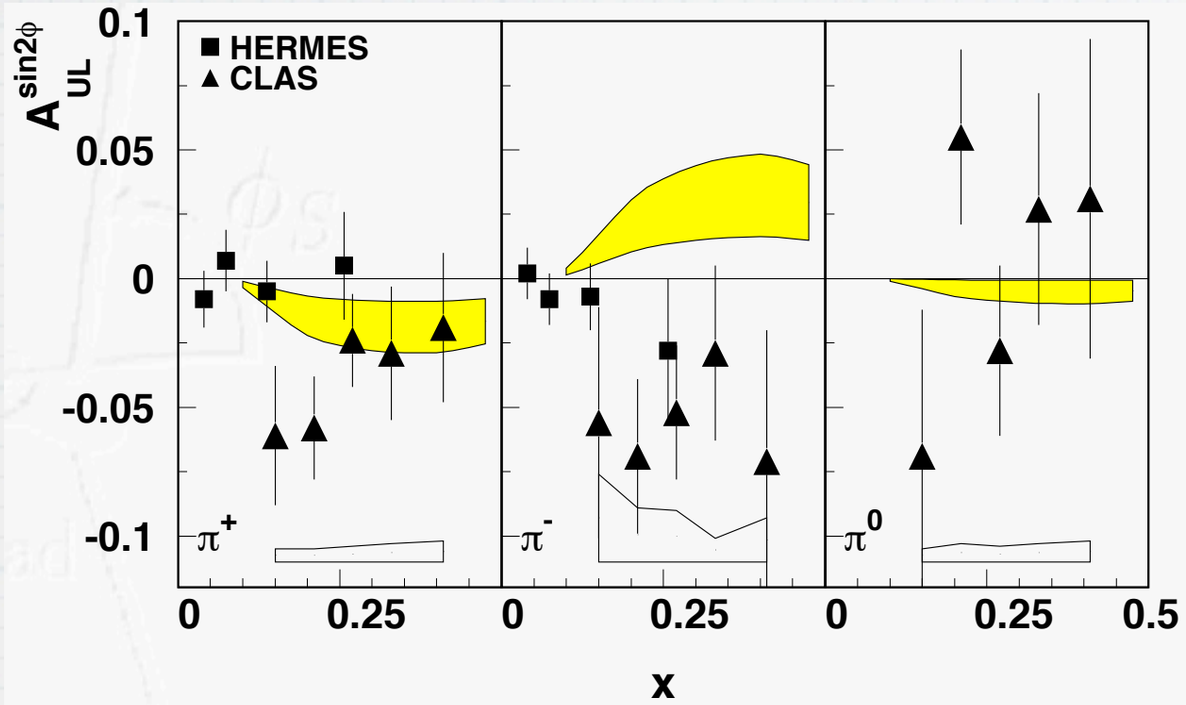
parton transverse momentum

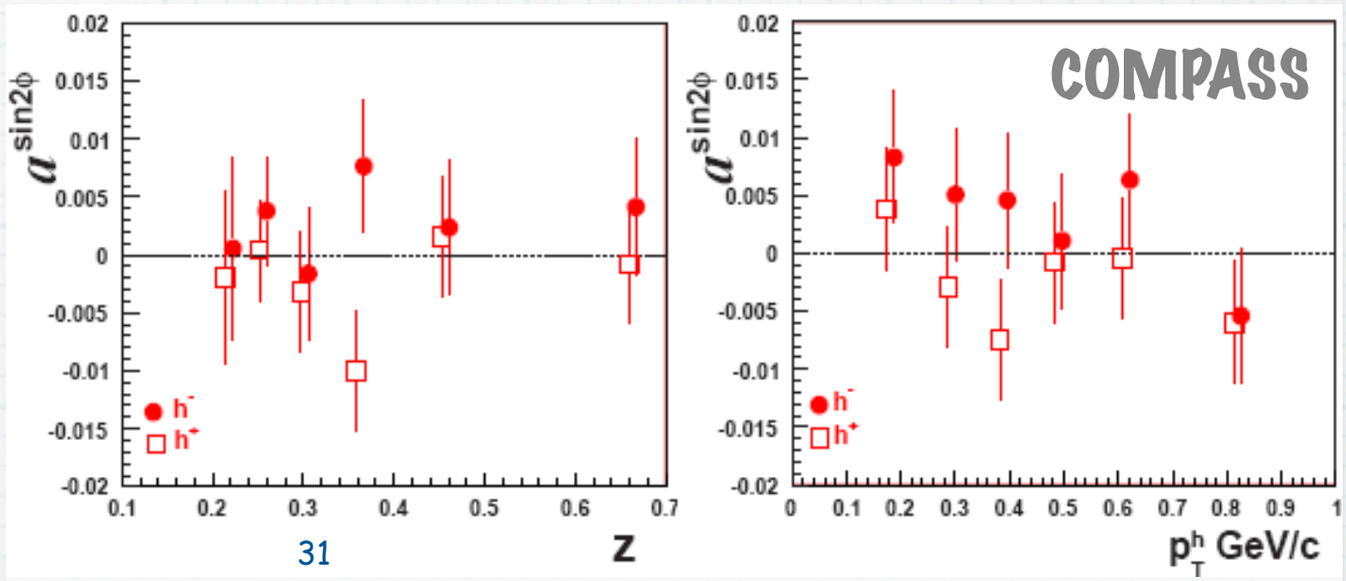




* chiral-odd > need the Collins FF or similar
* results consistent with zero

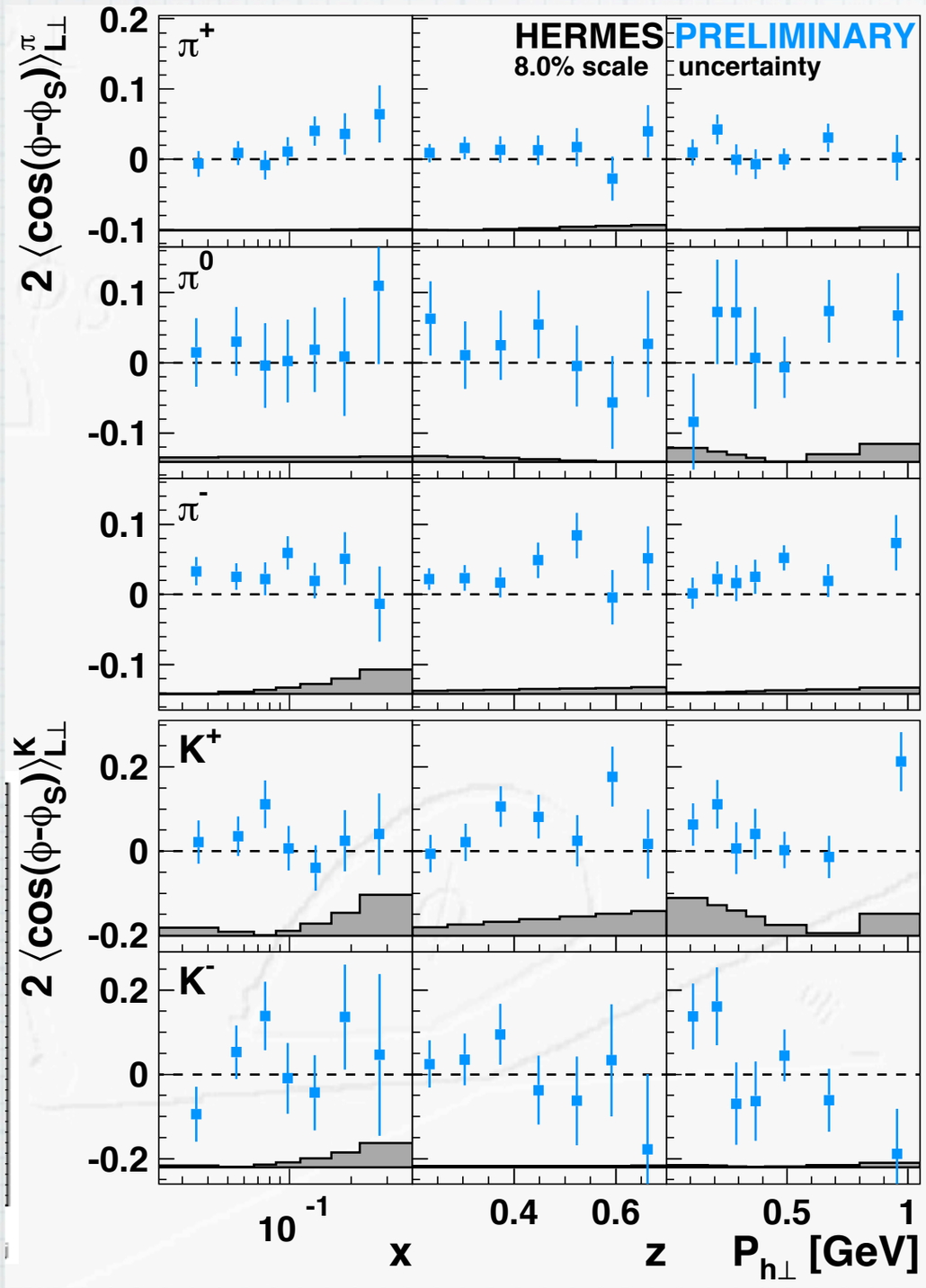
Pretzelosity

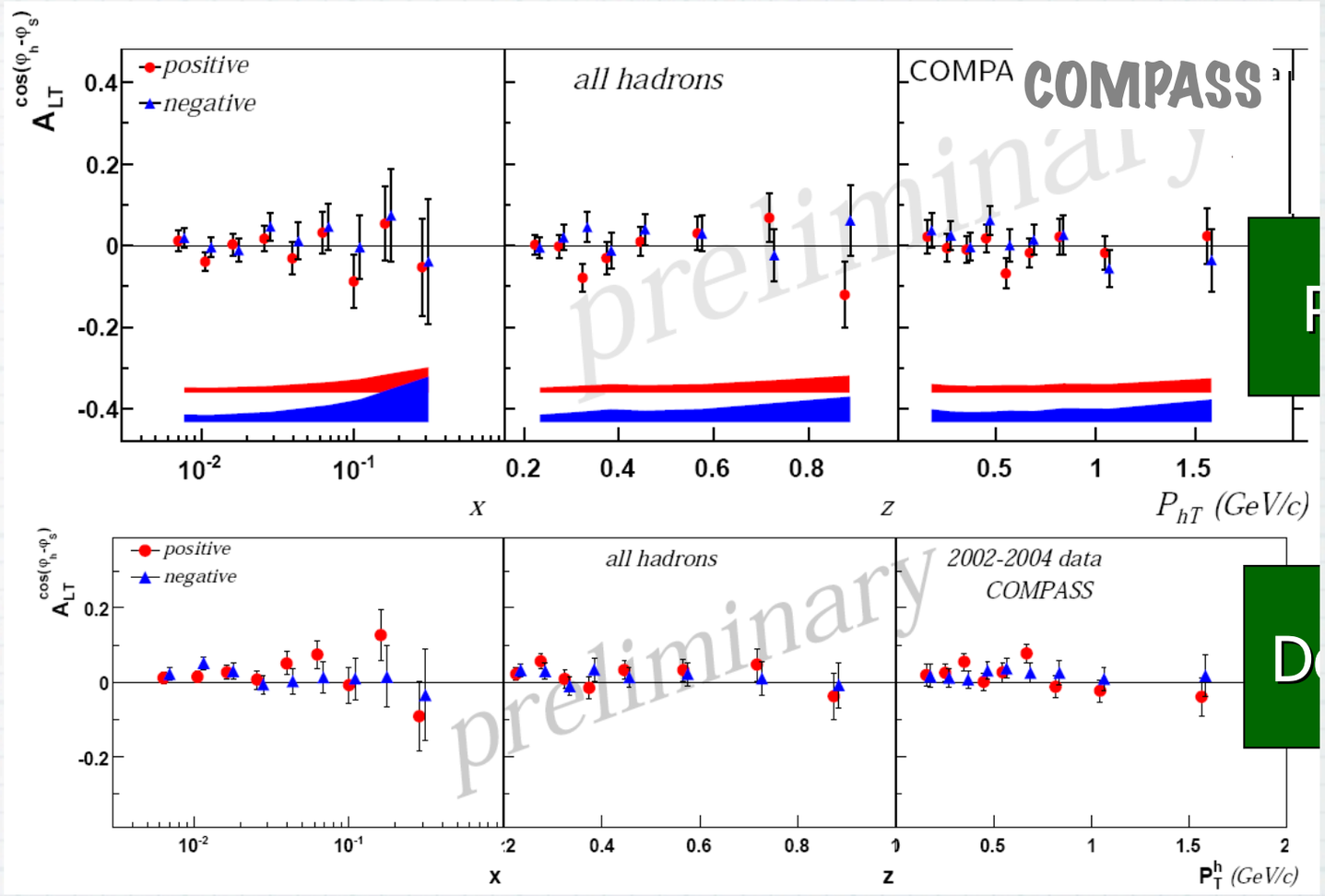


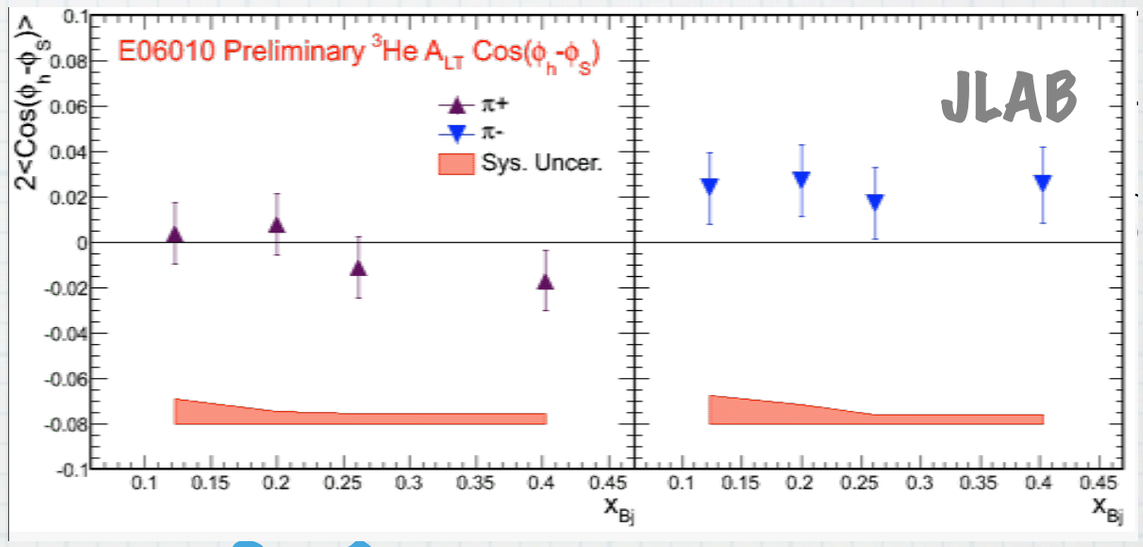


* chiral-odd > need the Collins FF or similar
* results consistent with zero at HERMES and COMPASS
* non-zero from CLAS?

worm gear UL

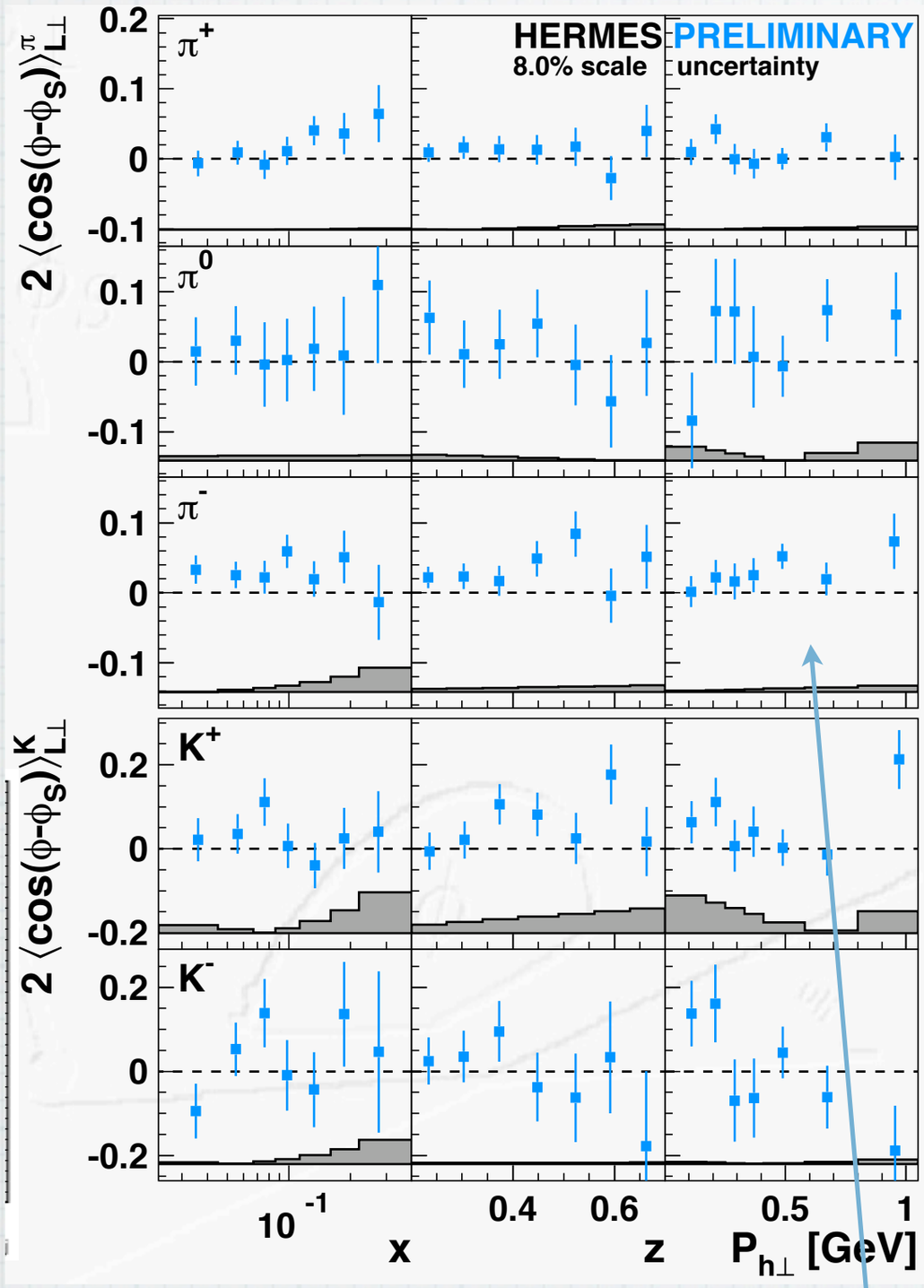


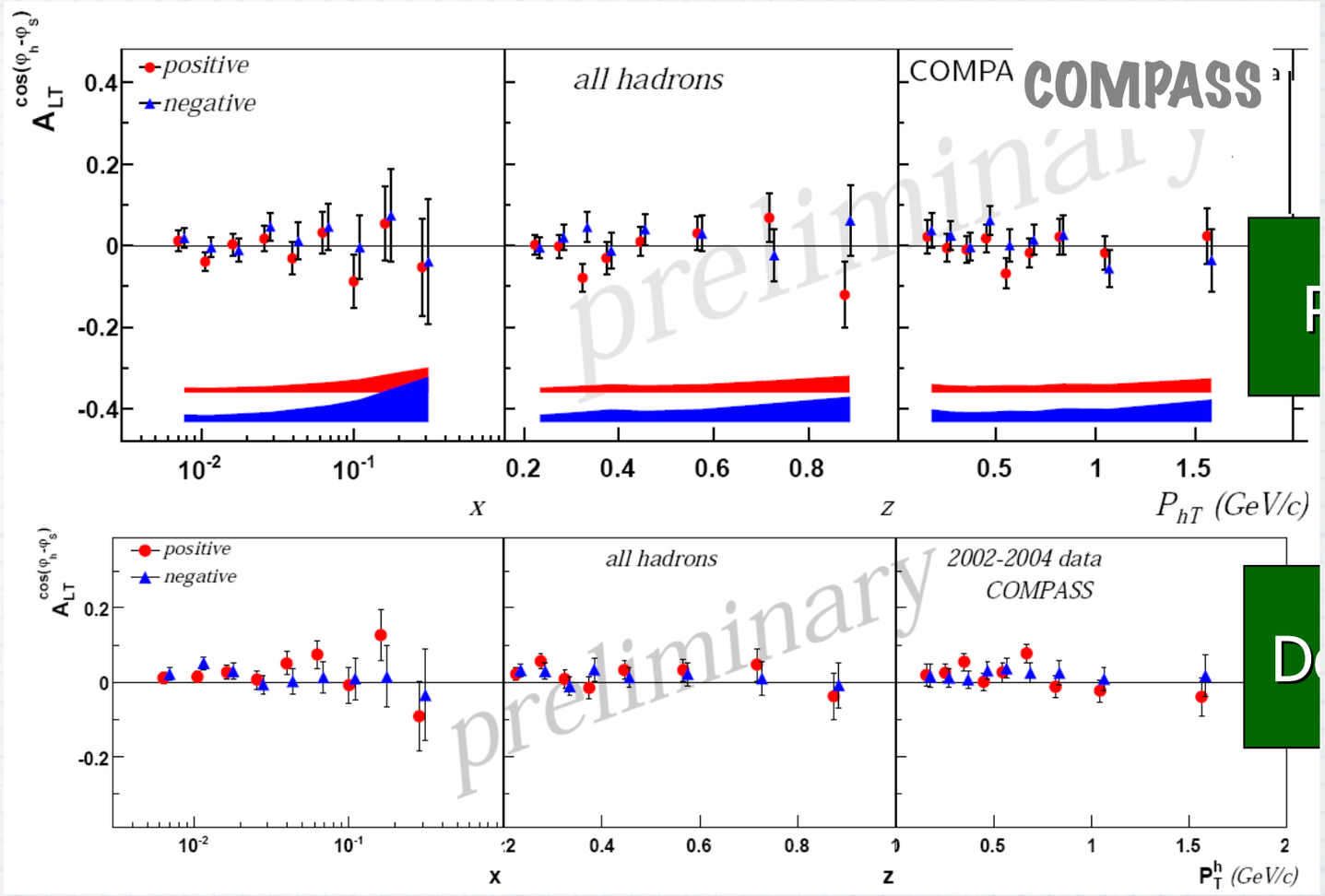


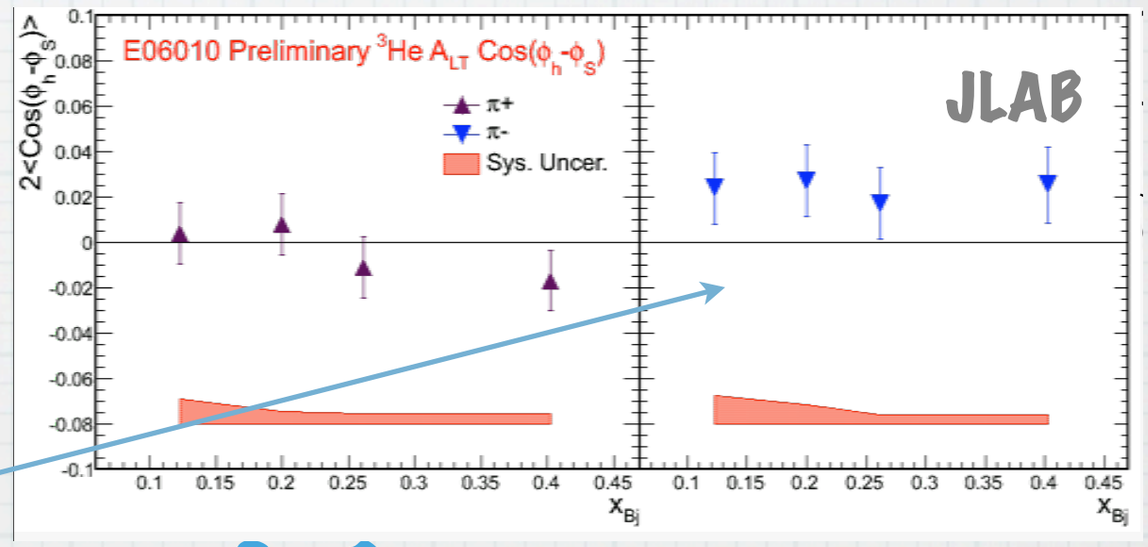


* results consistent with zero
  * hint for non-zero results?

worm gear LT







* results consistent with zero
  * hint for non-zero results?

worm gear LT

Summary

- To date, DIS experiments have played a crucial role in describing the proton structure
- Different reactions give complementary information: DIS, hadron and e+e- reactions are all needed to gain a complete picture of inner nucleon structure

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Thank you!

Summary